A Computational Framework for the Concurrent Evaluation of Thermal Comfort and Energy Use in Buildings

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Abstract

Despite the obvious importance of thermal comfort in the design of indoor environment, it is yet to be effectively integrated with design decision support tools. The reasons can be attributed, in part, to an absence of modular and flexible software architecture that can facilitate dynamic data transfer between energy performance, HVAC performance, and thermal comfort evaluation programs. However, mere timely provision of classical thermal comfort indicator may not sufficiently address the requirements of design support. Research has shown that the mathematical models of thermal comfort occasionally fail to accurately describe or predict thermal comfort in a variety of field settings outside the climate chamber even when the values of environmental and personal parameters are known. Thus, there is a critical need to provide a thermal comfort evaluation framework that, in addition to the algorithmic use of mathematical thermal comfort prediction models, would make use of the empirical knowledge base accumulated over the last 20 years from experiments around the world. A methodology used to refine thermal comfort predictions in commercial buildings by analyzing "matching" empirical data has been implemented.

To be effectively used as a design support tool, the modified thermal comfort indices combining the principles of physics and physiology with empirical results from field studies must be used to design indoor thermal environments which will achieve the twin objectives of providing a higher thermal satisfaction level and minimizing energy use. Toward that end, an active support strategy that works with other thermal applications of SEMPER to optimize the design of indoor thermal environment and provide a richer set of building thermal controls has also been implemented.

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1 Motivation and Background

1.1 INTRODUCTION

Enhancing thermal comfort is one of the main objectives of designing an indoor thermal environment. However, in spite of the many advancements in the field of indoor environmental science, dissatisfaction with indoor thermal environment remains the number one source of complaints among office workers (Federspiel 1998).

Providing thermal comfort involves control of environmental parameters such as temperature, humidity etc. through either an active or a passive mode of conditioning indoor thermal environment. Controlling environment through active means has important energy and financial implications as shown in *Table 1.1*. It shows construction and energy costs in the commercial building sector in this country. According to a study (Building Magazine 1996), 93% of all retrofit projects involved energy efficiency measures and 70% included measures to enhance indoor environmental quality (IEQ), thus emphasizing the importance of thermal comfort in building retrofit projects as well.

TABLE 1.1: 1996 Construction/Retrofit and Energy Cost in Commercial Building Sector

	New Construction Cost[a]	Energy Cost	Retrofit Cost
Commercial Building	$153.8 Billion (2.1% of U.S. GDP)[b]	$93.8 Billion[c] ($14.31/sq. m.)	$91.9 Billion[d]

a. All costs are in 1995 dollars
b. Total new building construction accounted for 5.4% of U.S. GDP (Department of Commerce 1996)
c. HVAC share was $28.1 billion or 30%. EIA, AEO 1998, December 1997
d. Department of Commerce 1995.

The Heating Ventilating and Air Conditioning (HVAC) industry in the US accounted for almost 30% of the energy consumed in the commercial building sector in 1995 (Department of Energy 1997) as shown in *Figure 1-1* below. To put this number in global perspective, this is equivalent to 4.49 x 10^{15} J, or 40% of Africa's total energy consumption (building, industry and transportation sector combined) for the same year, or the annual output of 250 baseload (1 GW each) nuclear power plants. This also results in about 150 million metric tons of carbon/year, or 2.7% of global carbon emissions. As the developing economies of China and India look toward improving their life-styles, they seek more energy intensive technologies to satisfy their increased thermal comfort demand. Their implications for global energy consumption will be significant considering that energy use has been projected to increase at an average annual rate of 4.5% from 1995 to 2020 (Department of Energy 1998).

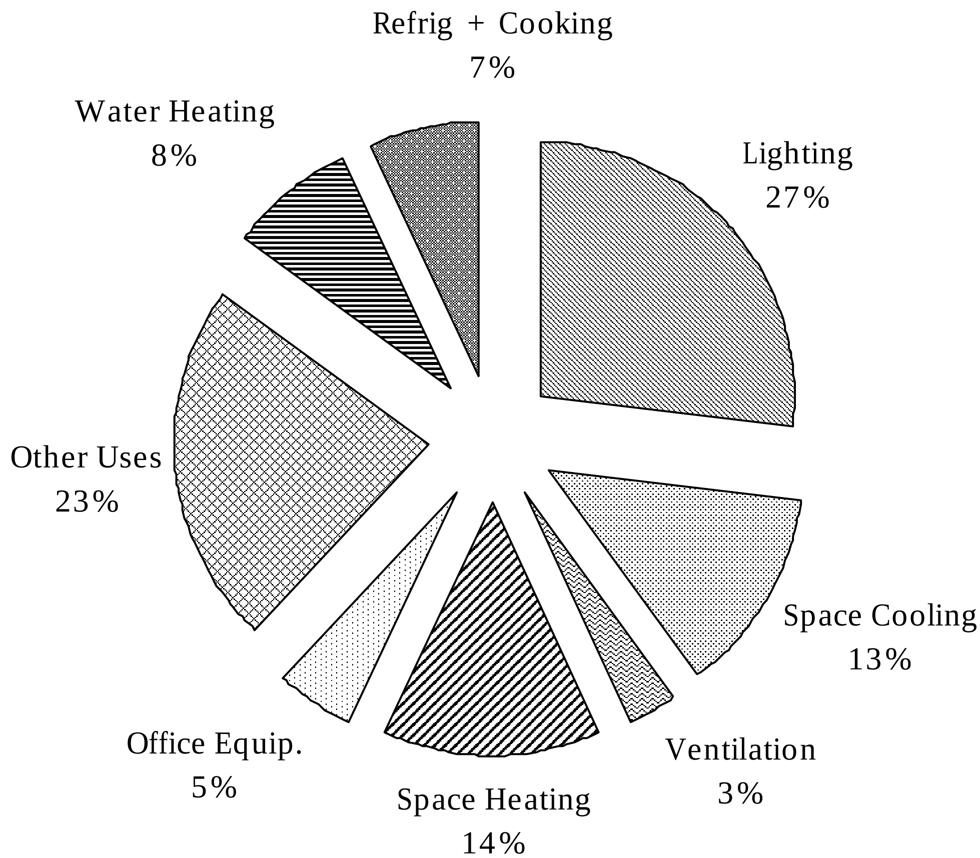


Figure 1-1: Distribution of energy use in commercial buildings in US

In an age of ever-decreasing energy prices and HVAC innovations, when human beings are spending a greater part of their lives in artificial climates, a minimum level of comfort in the workplace is considered *sine qua non*. At the same time, the measures taken to accomplish this task should be resource conserving. A balance is needed between the two seemingly contradictory issues of comfort through energy intensive means and sustainability. It is possible to provide a comfortable indoor environment by adopting due diligence in the design, operation and maintenance (O&M) of buildings and associated environmental systems. A design should consider energy conservation measures such as improved envelope insulation, reduced air infiltration (without compromising the provision of fresh air to building occupants), deployment of heat recovery and cogeneration systems, night-time setbacks, and use of renewable resources to minimize energy use and reduce concentration of greenhouse gases in the environment.

Despite the obvious importance of thermal comfort in the design of the indoor environment, it has not been integrated with design decision support tools. There is a pressing need to provide early feedback to the designers on the quality of thermal environment so that instead of promoting reliance on mechanical systems to create a comfortable indoor environment, crucial design decisions can be made which would reduce the dependence of buildings on mechanical systems. ASHRAE (1992) and ISO (1994) have standards that provide a numerical framework for predicting thermal comfort and at a minimum, designers should have access to information that would enable a simple comparison with the above standards for design evaluation and refinement.

It is difficult to find concrete empirical evidence relating thermal comfort to human health. It can be argued, however, that since exposure to extreme hot or cold environments over an extended period of time is harmful to human beings, it is likely that overall thermal comfort is worth striving for in relation to human health. Thermal discomfort has been identified as an extremely important factor in the perception of poor indoor air quality, which is a major scourge for building owners, clients, and energy service providers. There is also a large pool of occupants and workers who complain of poor indoor air quality, which may affect their ability to perform their tasks effectively and in some instances may be responsible for the sick building syndrome (SBS). The combined productivity loss resulting from poor indoor air quality has been estimated to be between 20 to 150 billion dollars (Fisk and Rosenfeld 1997).

From this discussion, it is evident that there is a clear need for developing an integrated design environment that can perform a dynamic evaluation of the indoor thermal environment. To address the challenges outlined above in a comprehensive manner, the solution must also address the discrepancies often found between the predicted and observed thermal comfort levels. This can be attributed to such non-quantifiable pyscho-social factors as motivation, expectation, culture, adaptability, job security and work stress (Mahdavi and Kumar 1996).

1.2 Status of Current Research

Efforts to address thermal comfort problems have largely been confined to either comfort chamber experiments (Fanger 1967, Houghten and Yaglou 1923, Nishi et al. 1975, Olesen et al. 1983, Rohles and Nevins 1971) or field experiments (Busch 1992, de Dear et al. 1991, Mallick 1994, Oseland 1994, Schiller et al. 1988).

ASHRAE (1994) invited proposals to develop a tool that would provide feedback to designers in evaluating indoor thermal environments. The outcome was an application (Fountain and Huizenga 1996) that can calculate thermal comfort indices based on the user input of environmental and personal parameters. Although this was a good first step, it fell well short of providing an integrated framework for early design support and modification capabilities to meet the stated design objective. One had to wait for the completion of design and then use a separate energy analysis tool to generate input parameters before performing a thermal comfort evaluation. The effort was in line with many other existing building performance evaluation stand alone packages, whose use is limited to experts seeking design verification or for standardizing field study calculations (de Dear and Schiller 1998).

The science of administering a thermal comfort survey together with the measurement and data-logging of essential thermal comfort parameters has made significant strides over the last two decades but there is still a critical need to provide a thermal comfort evaluation tool that would make use of the empirical knowledge base accumulated over the last 20 years from experiments around the world. A database compiled from 46 field studies consisting of 20,693 subjects in 160 different buildings provides a useful sample set for retrieving and using information to fine tune the design derived from any evaluation tool (de Dear 1998).

1.3 Research Problem

Designing an indoor work environment has commonly been viewed as an either/or dichotomy of energy conservation vs. human comfort. Despite considerable research in the field of thermal comfort, there is still insufficient support for concurrent evaluation of thermal comfort and energy performance in the early design process. The current research on thermal modeling tools and their integration with architectural design tools do not effectively support simulation-based architectural design decision making. In order to address this situation, there is an urgent need to provide a broad-based thermal simulation tool which can address the following problems facing researchers, designers and educators alike:

- The tools currently available either take a simplified thermal modeling approach which is inadequate to handle complex thermal parameters such as thermal mass, solar shading, radiation exchange, and natural ventilation or are inappropriate in early design stages because they require separate and detailed input.

- Current applications lack a simulation environment wherein there is a real-time collaboration by way of simultaneous calculation of thermal loads, HVAC loads, and thermal comfort indices. Such design and simulation environment will be a major step forward in ensuring comfortable indoor environments by making optimal use of a passive or active environmental control system.

- The lack of integration between the design environment and performance simulation tools remains a major challenge. Barring a few research efforts, most of the tools are single-platform, and generally single domain. They often use program specific languages with poor graphical user interface (GUI). As a result, there is little incentive to use simulation tools in the design process which, in the final analysis, affects the quality of the designed buildings. At present, simulation tools are being used by specialists predominantly for evaluating existing indoor thermal environments with very limited use in the design decision-making process. The existing knowledge base should become part of the architectural design process allowing trade-offs to be made on a contextual basis.

- There is a clear need to supplement algorithmic thermal comfort prediction with the results of thermal comfort field studies conducted around the world which have shown discrepancies between the predicted and observed thermal comfort values. A clearly formulated analytical approach relying on the results of the field study database as its knowledge base (ASHRAE 1995) would not only buttress the existing thermal comfort standards (ASHRAE 1992, ISO 1994) but also help reduce energy consumption and enhance the acceptance of indoor thermal environment.

- There is a growing evidence that indoor air quality is the prime suspect for the sick building syndrome (Mendell 1993, Brightman et al. 1997). Based on the extensive research performed in this field, it is fair to conclude that productivity and health problems are results of poor thermal and air quality conditions in indoor environments which can cause SBS and result in considerable financial losses (Fisk and Rosenfeld 1997, Kroner 1992).

1.4 Research Objectives

The thesis will critically examine two research areas that are germane to the quest for active, integrated design and simulation environments and continue to develop the computational framework of SEMPER (Simulation Environment for Modeling Performance) for multi-performance design and evaluation (Mahdavi 1996, Mahdavi et al. 1996, Mahdavi et al. 1997):

1. *Concurrent evaluation of interdependent performance agenda in the domain of thermal performance*

   Using the paradigm of structural homology, the Thermal Indices for COmfort Module (TICO) will work in collaboration with the NODEM (Mahdavi and Mathew 1995, Mathew 1996), BACH (Mahdavi and Wong 1998, Wong 1998) and HVAC module (Brahme 1995) to provide real-time feedback to the designer about the status of thermal environment.

2. *Knowledge-based support to further augment thermal comfort simulation engine*

   This thesis will explore approaches to predict thermal comfort in buildings employing various ventilation and air-conditoning strategies. This will be a field study based evaluative approach relying on the numerous field studies that have been performed over the last two decades (de Dear 1998).

   Subsequently, a more intelligent and energy efficient building control strategy has been developed using thermal comfort indices such as the Predicted Mean Vote (PMV). The resulting strategy can provide a higher level of satisfaction because the multi-variate algorithms governing the formulation of PMV are more inclusive than the traditional thermostat control which is typically dependent on just one variable—air temperature. More innovative control strategies based on customized personal environments can also be tested in tandem with the HVAC module under the SEMPER environment.

1.5 THE STRUCTURE OF DISSERTATION

This research effort will be organized under the following main categories:

1. The core domain knowledge in the field of thermal comfort will be discussed in *Chapter 2*. A brief review of the thermal comfort indices implemented in TICO will be provided. The heat balance (single node or steady-state and two-node or dynamic) models and the algorithms used to calculate the mean radiant temperature in an indoor environment will also be discussed.

2. The computational framework under which TICO has been implemented will be shown schematically in *Chapter 3*. The framework for dynamic data exchange among the various thermal performance modules (NODEM, HVAC, BACH and TICO) predicated on the shared and domain object model in SEMPER will also be discussed.

3. *Chapter 4* is devoted to the "active" design support that complements the main simulation engine of TICO to fine tune it. First, the knowledge-based support system, which has been developed to refine the results from quasi-deterministic thermal comfort algorithms with empirical data collected from thermal comfort field studies will be discussed. Second, the bi-directional inference implementation to help achieve the performance objectives of design will be explained.

4. In *Chapter 5*, TICO’s capabilities are demonstrated via illustrative examples. In a sequential fashion, TICO first calculates thermal comfort levels on a user-defined grid inside a building which is then adjusted to account for discrepacies in matching field studies using the methodology developed in *Chapter 4*. This is followed by a demonstration of "active" design/control strategy both at the TICO as well as SEMPER level.

5. *Chapter 6* outlines the main contributions of this thesis and formulates future research questions that were encountered during this research.

2 Physiology of Thermal Environment - Algorithms and Implementation

2.1 Prediction of Thermal Comfort and Thermal Sensation

2.1.1 Introduction

Thermal Indices for Comfort Module or TICO implements two algorithms (based on steady-state and dynamic model of human body) that are used to predict thermal comfort under a numerical framework. The thermodynamic processes taking place between the human body and the surrounding thermal environment are shown in *Figure 2-1* (ASHRAE 1997) as they form the basis of both the algorithms. Our perception of thermal comfort and the subsequent evaluation and acceptance of indoor thermal environment is a result of the heat generated by metabolic processes and the adjustments that the human body makes to achieve a thermal balance between our body and the environment.

Figure 2-2 shows the magnitude of heat losses taking place between human body and its surroundings for a person doing sedentary work in an office environment when both the air and the mean radiant temperature are maintained at 21°C (E Source 1993).

ASHRAE (1992) and ISO (1994) literature have identified the following six factors that influence the heat transfer between the human body and the surrounding environment as shown in *Table 2.1*.

2.1.2 Evaluation of Thermal Environment

In order to accurately predict thermal comfort using the two algorithms, one should be

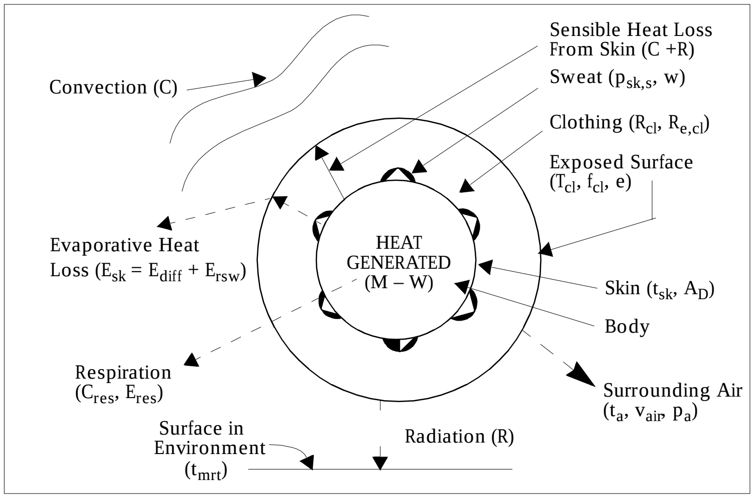


Figure 2-1: Cylindrical model of thermal interaction of human body and environment

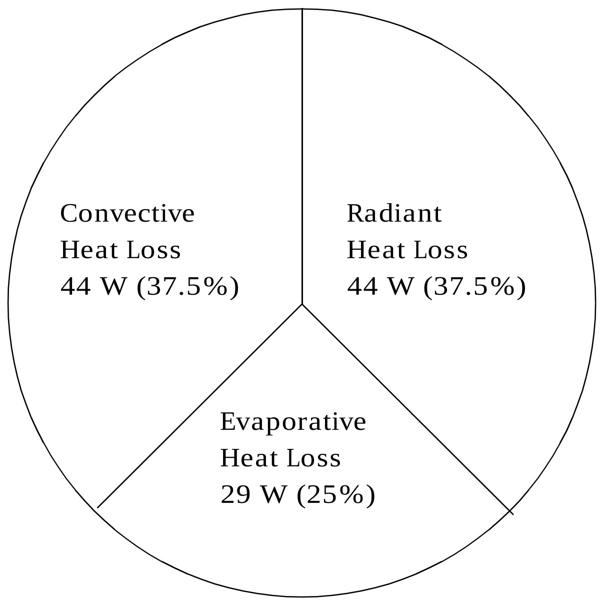


Figure 2-2: Heat Loss For a Sedentary Office Worker at 21°C

able to calculate the values of the six variables listed in *Table 2.1*. The values of all the variables except mean radiant temperature can either be specified as an input to TICO, or derived from other modules of SEMPER (see *Chapter 3*). Mean radiant temperature, however, calls for a different treatment because its exact value can only be calculated if the value of angle factors between the human body and various surrounding surfaces is known. A simplified technique for calculating mean radiant temperature in buildings has been implemented (Mahdavi and Mathew 1993b). It assumes that the human body can be reduced to a point for radiation exchange purposes and is applicable for calculating

TABLE 2.1: Thermal Comfort Parameters, their significance and energy implications

	Parameters	Significance	Design/IEQ Implications
Environmental	Air Temperature	most important parameter for determining thermal comfort	determines thermostat setpoints, sensible loads and influences the perception of IEQ
	Mean Radiant Temperature	key factor in the perception of thermal discomfort resulting from radiant asymmetry	radiant panels can reduce the requirement of conditioned air
	Relative Humidity	excessive dry or muggy conditions are immediately perceived as uncomfortable	enthalpy-based economizer, although difficult to control has good potential to save energy and provide greater thermal comfort
	Air Velocity	key factor in the perception of draft due to elevated air velocity	Can be used to reduce thermal discomfort in conjunction with passive design
Personal/Occupancy	Activity Level	poses a problem to designers if an indoor space has to be designed for people with different activity levels	determines thermal output of individuals which directly affects cooling/heating load of a conditioned space
	Clothing Resistance	important factor in the perception of thermal comfort; use of clothing to adjust to thermal environment is a good example of adaptive control.	In office environment, chair upholstery can increase the resistance by as much as 0.15 clo; difference in the clo values of male and female dresses should be taken into account

mean radiant temperature inside spaces enclosed by orthogonal planes. Although this introduces a small error in the calculation, it is not significant for the temperature range that is encountered in our daily indoor activities. Refer to *Appendix B* (Mean Radiant Temperature Analysis) for a discussion on angle factors and the calculation of mean radiant temperature.

The formulation (either empirical or exact) of principal heat transfer processes and the calculation of thermal comfort factors are not enough to predict thermal sensation accurately because of the highly personal interpretation of thermal sensation. But, it is possible to predict thermal sensation reasonably for many practical purposes based on the principles of heat transfer, human physiology and acclimatization (McIntyre 1980).

Thermal Comfort as defined by ASHRAE (1992) is "*that condition of mind in which satisfaction is expressed with the thermal environment*." In addition to the previously discussed independent environmental and personal variables influencing thermal response and comfort, other factors such as non-uniformity of the environment, visual stimuli, age, sex, outdoor climate, and circadian rhythms also have some effect but are generally considered to be secondary factors (ASHRAE 1997).

Much research has gone into the development of the models of thermal exchange between human body and the environment (*Figure 2-1*), and the subsequent physiological strain and perception of thermal sensation (Fanger 1970, Gagge et al. 1971). A mathematical description of the energy balance for the human body relies on a combined theoretical-empirical approach to describe the thermal exchanges with the environment. Fundamental heat transfer theory is used to describe the various mechanisms of sensible and latent heat exchange while certain coefficients describing these rates of heat exchange have been derived from experimental data (ASHRAE 1997).

In order to facilitate the design of better thermal environments, the subjective thermal sensation experienced by people must be translated to a numerical index. Because of individual differences, and the subjectivity involved while classifying thermal environment, it is impossible to specify a uniform thermal environment that will satisfy everyone. According to ASHRAE (1992), an indoor thermal environment should be able to satisfy at least 80% of the occupants in order to be termed acceptable. The total number of dissatisfied people in a thermal environment (≤ 20%) takes into account two sets of people whose union may be a null value:

a) those experiencing general discomfort (10%);

b) those experiencing local thermal discomfort because of conditions like asymmetric thermal radiation and draft (10%);

However, this standard of satisfying 80% of the occupants can be criticized. With the advancement in the HVAC industry and the associated ability to control the indoor climate at a micro level, it is possible to provide customized personal environments to meet thermal comfort needs of individual occupants. An advanced control system can complement and support the overall environmental system and help reduce the number of dissatisfied people to a minimum.

2.2 Thermal Comfort Indices

2.2.1 An Overview

Thermal sensation indices currently used by the environmental design professionals are briefly reviewed here. These indices have been used as benchmarks in various field studies to compare with actual results (Schiller 1990, Doherty and Arens 1988). They are also well documented in many technical papers and are part of ASHRAE's and International Standard Organization's (ISO) technical literature (ASHRAE 1997, ISO 1994). Algorithms to calculate the following thermal comfort indices has been implemented in TICO.

1. Effective Temperature or ET* (Houghten and Yaglou, 1923) was the first effort in developing an integrated thermal comfort index (combining the effects of air temperature, mean radiant temperature and relative humidity) and is still widely used in the design of indoor environment. Two environments with the same ET* evoke the same thermal response even though they may have different temperatures and humidities assuming that they have same air velocities. Calculation of ET* can be tedious, requiring the solution of multiple coupled equations to determine skin wettedness and the two-node model discussed later is used for the purpose.

2. ASHRAE's Standard Effective Temperature (SET*) is defined as the equivalent dry bulb temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature, t_{sk}) and thermoregulatory strain (skin wettedness) as in the actual test environment (ASHRAE 1997). SET* is a refinement of ET* wherein a standard set of conditions representative of typical indoor applications is used.

3. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) is based on a steady-state heat balance model of the human body that predicts the mean response of a large group of people on ASHRAE 7-point thermal sensation scale (assuming normal distribution). PMV is related to the imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort. *PPD* is a quantitative prediction of the number of thermally dissatisfied persons based on the value of PMV. The PMV-PPD model is widely used and accepted for the design and field assessment of comfort conditions (Fanger 1970).

4. Thermal Discomfort (DISC) and Thermal Sensation (TSENS) are determined using a 11-point numerical scale (ASHRAE 1997). After calculating the values of skin and

core temperature and skin wettedness, the two-node model uses empirical expressions to predict TSENS and DISC (see *Section 2.4.3*).

2.3 Fanger's Steady-State Model

2.3.1 General Remark

The steady-state model developed by Fanger assumes that the body is in a state of thermal equilibrium with negligible heat storage. The key assumption is that the body is in a state of thermal neutrality, i.e. there is no shivering, and vasoregulation is not considered because the core and skin are modeled as one compartment (ASHRAE 1997). At steady state, the rate of heat generation equals the rate of heat loss, and the energy balance is shown as:

$$M - W - E_{diff} - E_{rsw} - E_{res} - C_{res} = K = C + R \tag{2-1}$$

The terms in the above equation as well as those used later are described in *Appendix A* The critical assumption, that Fanger made, was that at a given activity level M, when the body is not far from thermal neutrality, the mean skin temperature (t_{sk}) and sweat rate (E_{rsw}) are the only two physiological parameters affecting heat balance. It should be noted that heat balance can be achieved in a wide range of environmental conditions but thermal comfort can only be achieved within a very small subset of those environmental conditions. Fanger used the following linear regression equations based on data from Rohles and Nevins to calculate values of t_{sk} and E_{rsw}:

$$t_{sk,\,req} = 35.7 - 0.028(M - W) \tag{2-2}$$

$$E_{rsw,\,req} = 0.42(M - W - 58.15) \tag{2-3}$$

2.3.2 The Comfort Equation

Equation 2-1 now can be rewritten in the following form after substituting *Equation 2-2* and *Equation 2-3* for the term ($C + R$) and the relevant terms for individual heat transfer processes. For a detailed explanation, readers are directed to the proposal document of this dissertation (Kumar 1995). This is also known as the general comfort equation:

$$(M-W)-3.05\times10^{-3}[5733-6.99(M-W)-P_a]-0.42[(M-W) -58.15]-1.7\times10^{-5}M(5867-P_a)-0.0014M(34-t_a) = 3.96\times10^{-8}f_{cl}\times[(t_{cl}+273)^4-(t_{mrt}+273)^4]-f_{cl}h_c(t_{cl}-t_a) \tag{2-4}$$

For any type of clothing and any type of activity, *Equation 2-4* will be able to calculate all reasonable combinations of air temperature, air humidity, mean radiant temperature and air velocity which will create optimal thermal comfort for persons under steady state conditions (Fanger 1970). This equation assumes that all sweat generated is evaporated (eliminating clothing moisture permeability as a factor in the equation), which is valid for normal indoor clothing worn in typical indoor environment with low or moderate activity levels.

2.3.3 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

PMV predicts the mean value of thermal sensation votes of a large group of people on the 7-point thermal sensation scale which has already been discussed. *PMV* represents the statistical relation between physiological response of the thermoregulatory system to the thermal sensation votes collected from more than 1300 subjects. Mathematically, it can be represented by *Equation 2-5*. By setting $PMV = 0$, we can reduce *Equation 2-5* to *Equation 2-4* (general comfort equation). Fanger linked PMV with the concept of thermal load (the term within the curly brackets in *Equation 2-5*) that is defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of t_{sk} and E_{rsw} at the actual activity level.

$$PMV = (0.303e^{-0.036M}+0.028)[(M-W)-3.05\times10^{-3}\times [5733-6.99(M-W)-P_a]-0.42\times((M-W)-58.15) -1.7\times10^{-5}M(5867-P_a)-0.0041M(34-t_a) -(3.96\times10^{-8}f_{cl})\times[(t_{cl}+273)^4-(t_{mrt}+273)^4]-f_{cl}h_c(t_{cl}-t_a)] \tag{2-5}$$

Before PMV can be calculated, clothing temperature (t_{cl}) is found by iteration using Newton-Raphson method from *Equation 2-6* and substituted in *Equation 2-5*:

$$t_{cl} = 35.7-0.028(M-W)-I_{cl}[3.96\cdot10^{-8}f_{cl} ((t_{cl}+273)^4-(t_{mrt}+273)^4)+f_{cl}h_c(t_{cl}-ta)] \tag{2-6}$$

The *PMV*-index predicts the mean value of the thermal votes of a large group of people exposed to the same environment but individual votes are scattered around this mean value and it is useful to predict the number of people likely to feel uncomfortably warm or cool. The *PPD*-index establishes a quantitative prediction of the number of thermally dissatisfied persons. In other words, it predicts the percentage of people who would be dissatisfied with the thermal environment i.e. those voting hot (+ 3), warm (+ 2), cool (-2) or cold (-3) on the 7-point thermal sensation scale.

$$PPD = 100 - (95 \cdot e^{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)}) \tag{2-7}$$

The relationship between PMV and PPD is shown in *Figure 2-3* and can also be used to calculate PPD, if the value of PMV is known.

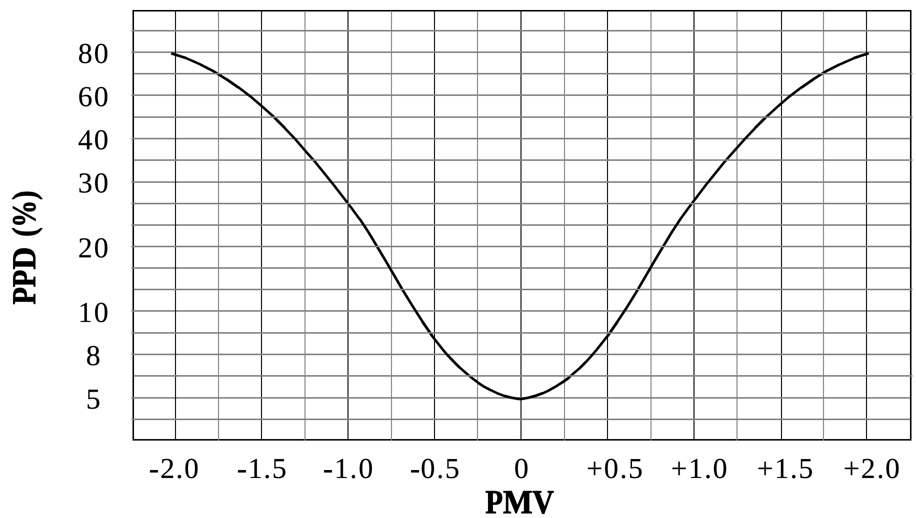


Figure 2-3: Curve to interpolate PPD as a function of PMV

2.4 GAGGE'S TWO-NODE MODEL (2NM)

2.4.1 GENERAL DESCRIPTION

The PMV model is only useful for predicting steady-state comfort responses. A comprehensive thermal comfort analysis also calls for the prediction of physiological responses to transient conditions, at least for low and moderate activity levels in cool to very hot environments (Gagge et al. 1971, 1986).

The two-node model represents the body as two concentric thermal compartments that represent the skin and core of the body. The skin compartment is assumed to be 1.6 mm thick and its mass (about 10% of the total body) depends on the amount of blood flowing through it for thermoregulation (Gagge et al. 1971). The key assumptions in this model are that conductive heat exchange from the skin is negligible; the temperature in each compartment is uniform; metabolic heat production, external work and respiratory heat losses are associated with the core compartment; and the core and skin compartments exchange energy passively through direct contact and through the thermoregulatory controlled peripheral blood flow. The thermal model is described by two coupled heat balance equations, one applied to each compartment. The variables used in the following equations can be looked up in Appendix 1 (Glossary of Terms).

$$S_{cr} = M - W - (C_{res} + E_{res}) - Q_{cr,sk} \tag{2-8}$$

$$S_{sk} = Q_{cr,sk} - (C + R + E_{sk}) \tag{2-9}$$

The rate of heat storage in the body equals the rate of increase in internal energy which can be written separately for each compartment in terms of thermal capacity and time rate of change of temperature in each compartment:

$$S_{cr} = (1 - \alpha) m c_{p,b} (dt_{cr} / d\theta) / A_D \tag{2-10}$$

$$S_{sk} = \alpha m c_{p,b} (dt_{sk} / d\theta) / A_D \tag{2-11}$$

Equation 2-10 and *Equation 2-11* can be rewritten by writing energy balance equations on the core (*Equation 2-12*)and skin (*Equation 2-13*):

$$M + M_{shiv} = \text{Work} + Q_{res} + (K + m_{bl} c_{p,bl})(t_{cr} - t_{sk}) + W_{cr} c_{cr} \frac{dt_{cr}}{d\theta} \tag{2-12}$$

$$(K + m_{bl} c_{p,bl})(t_{cr} - t_{sk}) = Q_{dry} + Q_{evap} + W_{sk} c_{sk} \frac{dt_{sk}}{d\theta} \tag{2-13}$$

Equation 2-12 and *Equation 2-13* can be rearranged in terms of $dt_{sk}/d\theta$ and $dt_{cr}/d\theta$ and numerically integrated with small time steps (10 to 60 sec.) either from initial conditions or previous values to find t_{cr} and t_{sk} at any time.

2.4.2 Effective Temperature (ET*)

The effective temperature (*section 2.2.1 on page 11*) is defined in terms of operative temperature (t_o), and hence combines the effect of three parameters (t_{mrt}, t_a and P_a) into a single index. Since the slope of a constant ET* depends on skin wettedness (w), which is calculated by solving multiple coupled equations in the 2NM, and permeability index (i_m), effective temperature may depend on the clothing of a person and the activity level for a given temperature and humidity. ET* can now be calculated by solving the following equation:

$$ET^* = t_o + wi_m LR(P_a - 0.5P_{ET,s}) \tag{2-14}$$

2.4.3 TSENS AND DISC

After calculating values of t_{sk}, t_{cr} and w, the model uses empirical expressions to predict thermal sensations (*TSENS*) and thermal discomfort (*DISC*). These indices are based on 11-point numerical scales, where positive values represent the warm side of neutral sensation and negative values represent the cool side. Two extra terms for ± 4 (very hot/cold) and ± 5 (intolerably hot/cold) have been added to the PMV scale.

TSENS is defined in terms of deviations of mean body temperature t_b from cold and hot set points representing the lower and upper limits for the zone of evaporative regulation: $t_{b,c}$ and $t_{b,h}$ respectively. The value of these set points depends on the net rate of internal heat production and are calculated by:

$$t_{b,c} = (0.194/58.15)(M - W) + 36.301 \tag{2-15}$$

$$t_{b,h} = (0.347/58.15)(M - W) + 36.669 \tag{2-16}$$

TSENS is then determined by:

$$TSENS = \begin{cases} 0.4685(t_b - t_{b,c}) & t_b < t_{b,c} \\ 4.7\eta_{ev}(t_b - t_{b,c})/(t_{b,h} - t_{b,c}) & t_{b,c} \le t_b \le t_{b,h} \\ 4.7\eta_{ev} + 0.4685(t_b - t_{b,h}) & t_{b,h} < t_b \end{cases} \tag{2-17}$$

where η_{ev} is the evaporative efficiency (assumed to be 0.85).

Thermal discomfort is numerically equal to *TSENS* when t_b is below its cold set point $t_{b,c}$ and is related to skin wettedness when body temperature is regulated by sweating:

$$DISC = \begin{cases} 0.4685(t_b - t_{b,c}) & t_b < t_{b,c} \\ \dfrac{4.7(E_{rsw} - E_{rsw,req})}{E_{max} - E_{rsw,req} - E_{diff}} & t_{b,c} \le t_b \end{cases} \tag{2-18}$$

where $E_{rsw,req}$ is calculated as in Fanger's model.

3 Implementation and Integration of TICO in SEMPER

3.1 ARCHITECTURE AND ELEMENTS OF SEMPER

3.1.1 OVERVIEW

SEMPER is an active, multi-aspect prototype design environment (Mahdavi 1996, Mahdavi et al. 1996) that is being developed to address some of the limitations documented extensively in the literature (Mathew 1996). It incorporates an object-oriented, space-based shared building representation, with dynamic links to different building performance evaluation applications. It is thereby intended to provide computational support for the evaluation of buildings across multiple performance mandates concurrently, with a view toward achieving total building performance and systems integration.

Figure 3-1 shows the architecture of SEMPER and its primary components:

- a shared object model (SOM), which encapsulates a space-based representation of a building;
- simulation modules that implement individual domain knowledge using application specific object model representations of the building;
- a database that stores shared object model of the building and facilitates the derivation of domain object models (DOM);
- a user interface that includes a traditional "CAD system" and other interface widgets for accepting building simulation parameters.

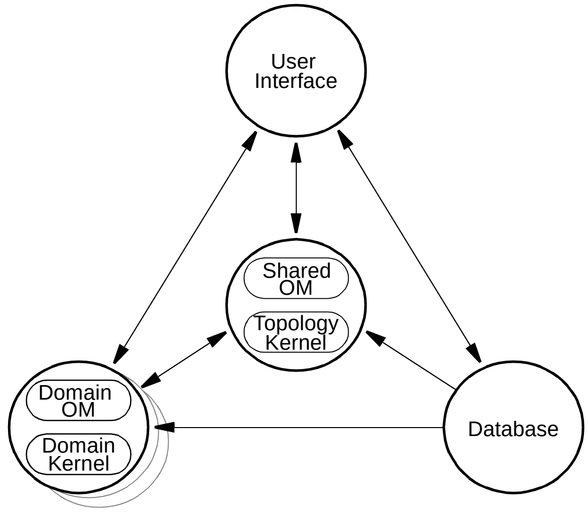


Figure 3-1: Schematic representation of the architecture of SEMPER

The first phase of the development of SEMPER incorporates seven performance simulation modules, as shown in *Table 3.1*. Most of these simulation modules are under various stages of development. A working prototype of the three thermal modules of SEMPER (NODEM, BACH and TICO) was used to test this work by simulating a conceptual building design, operating in passive mode (Mahdavi et al., 1997). A detailed description of that particular simulation along with the results is discussed in *Section 5.3*.

TABLE 3.1: Performance modules in SEMPER

Module	Modeling Technique	Performance Indicators
Thermal Analysis (NODEM)	Grid-based nodal heat-balance	Heating, cooling, electrical loads; Space temperature profiles
HVAC Systems (HVAC)	Modular, component-based approach	HVAC system energy consumption; fuel consumption
Air flow (BACH)	Hybrid multi-zone and CFD, using grid-based nodal network	Air flow patterns and quantities
Thermal Comfort (TICO)	Algorithmic routines for numeric indicators; knowledge-based system for thermal design refinement	Indicators of thermal comfort (PMV-PPD, SET, TSENS, and DISC)
Daylight and elec. light (LUMINA)	Discretized sky model; inter-reflection based on radiosity	Spatial distribution of luminance and illuminance levels
Acoustics (CASCADE)	Hybrid stochastic approach combining features of sound particle models and statistical energy distribution analysis	Sound pressure level distribution, parameters of the reverberant field
Life-cycle Assessment (ECOLOGUE)	Comprehensive eco-analysis (production, construction, operation and decommissioning phases of building) using eco-balance methods	First and Life-cycle costs, payback periods; Loads to natural resources

3.2 STRUCTURAL HOMOLOGY AND INTEGRATION

3.2.1 GENERAL REMARKS

One of the major obstacles facing the integration of detailed simulation methods with "CAD systems" is the incongruent nature of building representation in the two situations. Quite often, this discrepancy produces applications that are brittle, inelegant and contrived. This either a) results in the development of an application-specific language to facilitate the input of all the information available for performing detailed simulation, thereby adding another layer of complexity to the application, or b) requires a geometric interpreter to transfer CAD data into a format that can be interpreted by the applications.

SEMPER adopts a semantically enriched space-based, object-oriented building model. NODEM's representation for node-based heat balance calculation is practically homologous to this model. This allows (as illustrated in *Figure 3-2*) for the discretization of spaces into cells, and automatic creation of the homologous nodal structure in NODEM, which is then adapted for TICO. Since the environmental parameters required to run thermal comfort simulations are calculated by other thermal modules and transmitted to TICO via NODEM using the same nodal representation, the user can get feedback on the prevailing thermal comfort conditions for each node in the building.

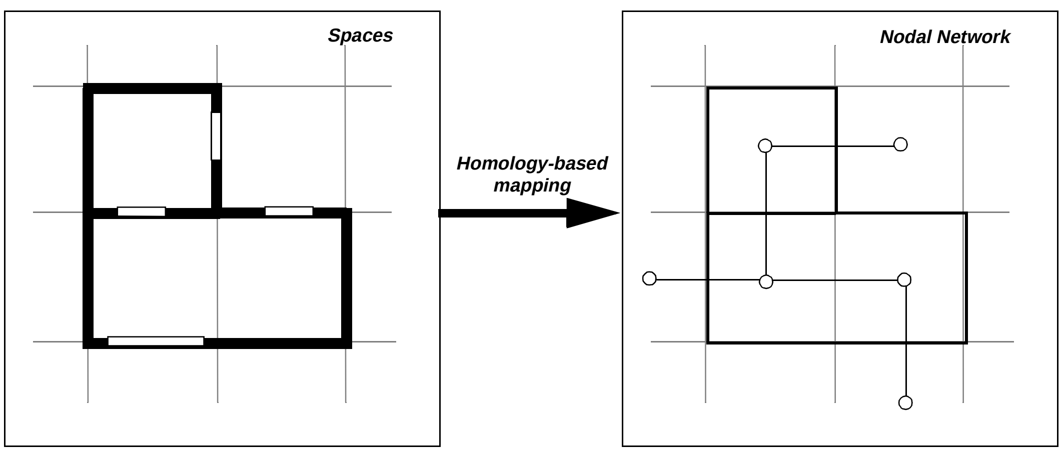


Figure 3-2: Derivation of Nodal Network from the homologous building design

3.2.2 INTEGRATED THERMAL MODELING IN SEMPER

3.2.2.1 Overview

One of the primary objectives of this research was to address the lack of integration which has led to the use of thermal comfort applications as stand alone tools. There was an absence of an application framework which would have enabled direct input of environmental parameters into thermal comfort applications. To realize this objective, TICO was designed as part of an integral thermal design environment comprising NODEM, BACH and HVAC module. The entire schema is shown in *Figure 3-3*.

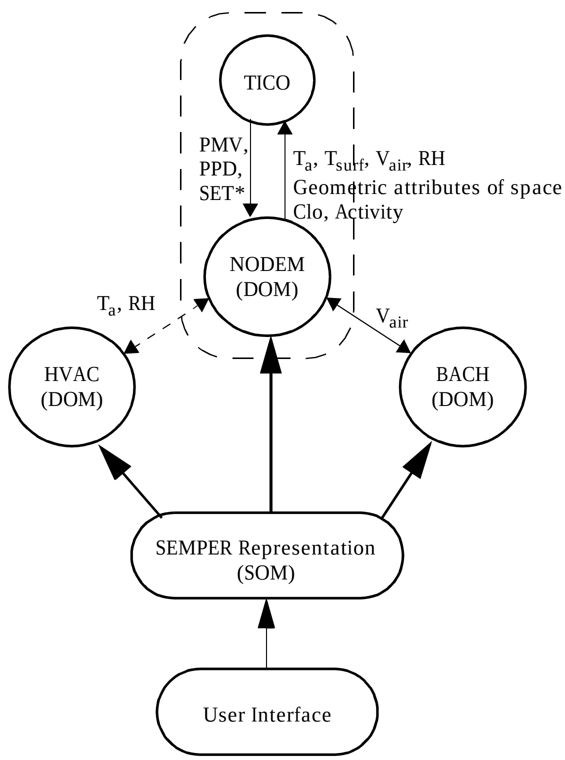


Figure 3-3: Interaction Between Thermal Modules of SEMPER

3.2.2.2 Algorithmic Implementation of Steady-State and Two-Node Model in TICO

As shown in *Figure 3-3*, TICO gets geometric and thermal attributes of space from NODEM. Support for clothing resistance and activity level input comes in the form of pre-defined libraries which are described in greater detail in *Chapter 4*. A schematic diagram showing the steps leading up to the calculation of thermal comfort indices in TICO is shown in *Figure 3-4*.

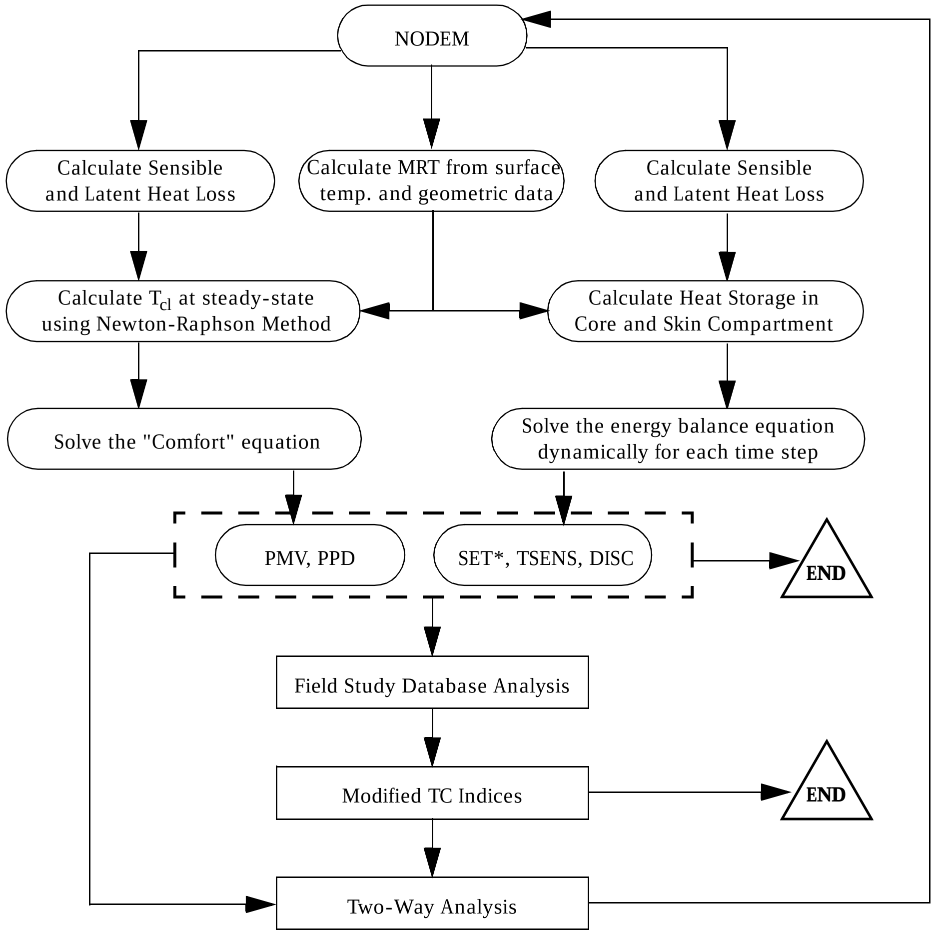


Figure 3-4: Flow Chart Showing Calculation Sequence in TICO

The first step common to both single (steady-state) and two-node (dynamic) model is the calculation of mean radiant temperature for the space from the geometrical attributes of space and the surface temperatures.

For the calculation of PMV and PPD, the following sequence of events take place:

1. Heat loss by water diffusion through skin is calculated;

2. The mean skin temperature and the sweat rate—the two physiological parameters influencing heat balance are then calculated;

3. This is followed by the calculation of evaporative and convective heat loss component from respiration;

4. The heat loss by conduction as a result of the difference in skin temperature and temperature of clothing is then calculated;

5. The surface temperature of clothing (t_{cl}) is then calculated for steady state scenario. If there is no convergence then the program requests another set of input parameters from the user;

6. Once t_{cl} is calculated, heat loss by convection from the outer clothing surface to the ambient environment is calculated;

7. In the final step, the "comfort equation" is solved and the Predicted Mean Vote and Predicted Percentage Of Dissatisfied is calculated.

The two-node model requires the implementation of the following steps:

1. Sensible heat exchange between human body and its surrounding is first calculated. This requires the calculation of: i) heat transfer from the skin surface, through the clothing insulation to the outer clothing surface via conduction, convection, and radiation and ii) heat transfer from the outer clothing to the environment by convection and radiation. Simultaneously, *Operative Temperature*, which is the weighted average of dry-bulb and mean radiant temperatures is also calculated;

2. Next, skin wettedness which is strongly correlated with warm discomfort and is also a good measure of thermal stress is calculated. Evaporative heat loss from skin, which is affected by the difference between the water vapor pressure at the skin surface and in the ambient environment and the amount of moisture on the skin is then calculated;

3. Respiratory heat losses (both sensible and latent) is then calculated;

4. The program then uses a mathematical framework for evaluating regulatory signals and responses (cold and warm) from skin and core compartments;

5. The thermoregulatory signals and the resulting strain on the human body is dealt by increasing or decreasing the volume of skin blood flow for heat transport;

6. Finally, both the core and skin temperature are solved at any time using numerical integration for a specified time of exposure. Individual energy flows and the thermoregulatory responses are recalculated for each time step since they are functions of skin and core temperature. The model then uses empirical expressions to calculate thermal sensations (TSENS) and thermal discomfort (DISC).

3.2.2.3 The Integration Framework

The relationship between shared object model and domain object model and the information flow between thermal modules is described in this section. The main components of this framework are:

- The *object model* is shown in *Figure 3-5*. It shows the objects from SOM relevant for thermal comfort simulation and their relationship to those domain objects of NODEM that are used when performing thermal comfort simulation. For a detailed treatment of NODEM's object schema, see Mathew and Mahdavi 1998.

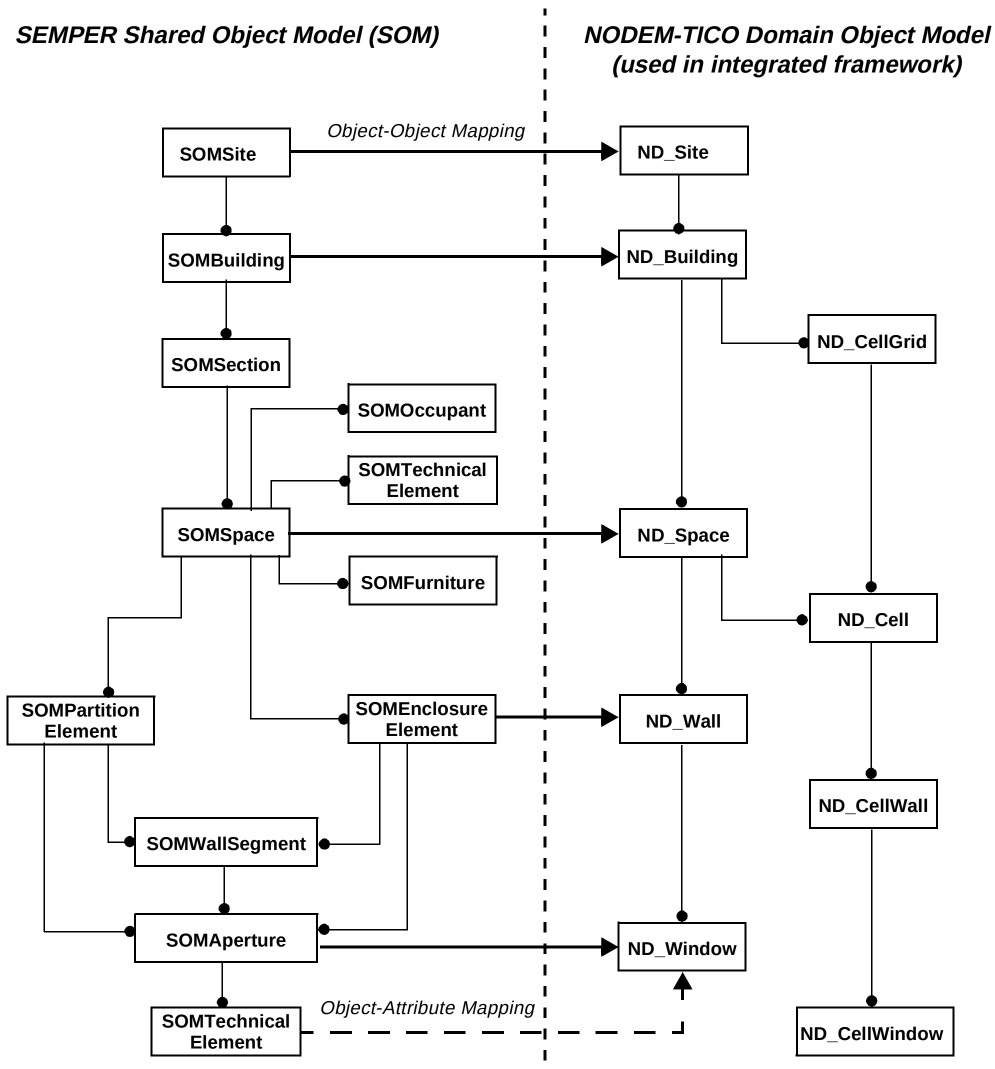


Figure 3-5: Object Model Schema of SEMPER

- In the order of increasing complexity, *Table 3.2* shows the key functions implemented in TICO that are called by NODEM to perform three kinds of thermal comfort analysis.

TABLE 3.2: Main Functions of TICO

TICO Functions	Operations
CalcPointTicoData	this function gets called at each time step by NODEM as it iterates through each space. It is the main engine of TICO that calculates thermal comfort indices from environmental and personal parameters passed as arguments.
PerfKBAnal	performs case-based analysis by first comparing the arguments against field study database, picking relevant case studies and then making quantitative recommendations.
PerfBidirAnal	recommendations made by PerfKBAnal function leads to the formulation of the optimization problem. This function uses heuristics and the dependency between design and performance variable to suggest refinements in the design or control strategy for the building.

  The first function forms the core capability of TICO in terms of calculating the quasi-deterministic predictive thermal comfort indices based on the modeling of human body. It is illustrated in greater detail via a flow chart in *Figure 3-4*. The second and third functions are discussed in the next chapter.

- *Table 3.3* shows the input and output data for each node that are necessary for creating the dynamic linkages between thermal modules of SEMPER and predicting the thermal comfort level on a dynamic basis.

Within this framework, each application has a number of application-specific objects within the object model. The dynamic links between applications occur at the object model level avoiding direct links between application objects. The use of a shared object model, with independent domain object model for each application, allows the individual applications to be developed fairly independently, while still communicating in a coherent and effective way.

The input and output data of *Table 3.3* is represented graphically in *Figure 3-6* (adapted from Wong 1998). As discussed earlier, NODEM acts as a conduit for TICO to communicate with other thermal modules.

TABLE 3.3: Input and output data for various thermal modules in SEMPER

Module	Input Data	Output Data
NODEM	Supply air temperature (t_s) Return air temperature (t_r) Volume flow of supply air (V_s) Volume flow of return air (V_r)	Air temperature (t_a) Surface temperatures (t_{surf}) Volume flow Relative humidity
HVAC	Volume flow (V_{node}) Relative humidity (RH_{air}) Air temperature	Supply air temperature Return air temperature Moisture content of supply air ($H_2O_{(s)}$) Volume flow of supply air Volume flow of return air
BACH	Air temperature Volume flow of supply air Volume flow of return air Moisture content of supply air	Volume flow Relative humidity
TICO	Activity level (Act)- direct input Clothing resistance (Clo)- direct input Air temperature - from NODEM MRT (t_{mrt})- derived from NODEM Relative humidity - from NODEM Air velocity (V_{air})- direct input or NODEM	Predicted Mean Vote (PMV) Predicted Percentage of Dissatisfied (PPD) Standard Effective Temperature (SET*)

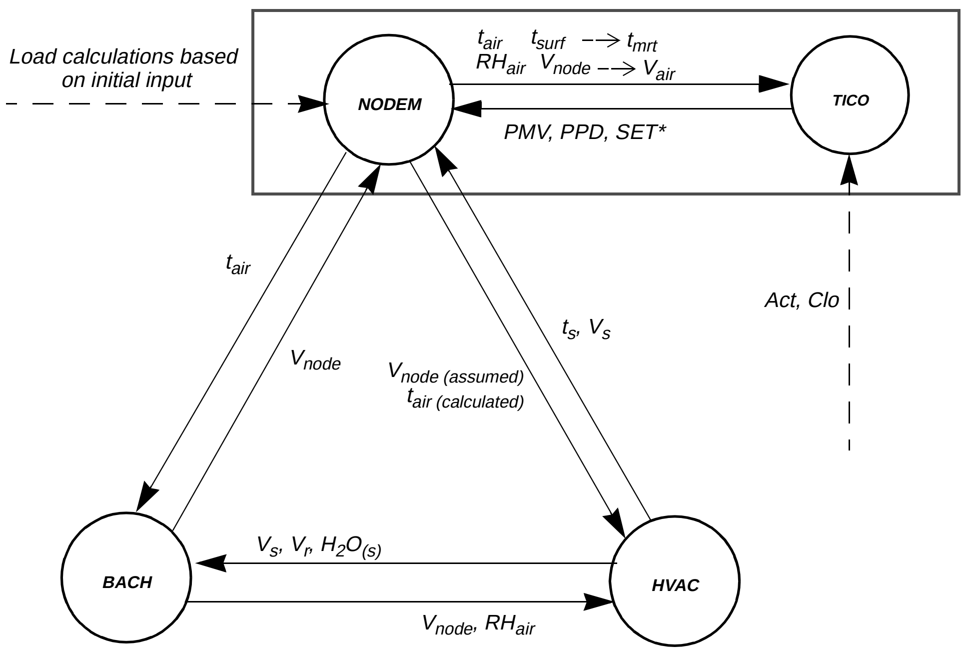


Figure 3-6: Dynamic Model showing events and states for various thermal modules in SEMPER

4 "Active" Design Support for Building Design and Control

4.1 Rationale

After completing a comprehensive review of the existing literature in the field of thermal comfort (see *Appendix C*), it was felt that the mathematical formulations to calculate thermal comfort indices needed refinement and enrichment in order to capture certain complex aspects of thermal comfort. The most serious shortcoming of these models is its failure to accurately describe or predict thermal comfort in a variety of field settings outside the climate chamber even when the values of environmental and personal parameters are known (de Dear and Auliciems 1985, Schiller et. al. 1988, Busch 1992). The challenge was to come up with a thermal comfort evaluation methodology that is able to predict human responses that are in closer agreement with the results of the field studies conducted in the natural ventilated buildings of tropical climates where these discrepancies are most pronounced. This would help bridge the gap so often found between the predicted and observed thermal sensation by analyzing and abstracting the cumulative knowledge gained over the years from empirical experiments. Key factors responsible for the above mentioned discrepancies between comfort model predictions and the results of field studies are (Mahdavi and Kumar 1996):

- difficulties in accurate estimation of heat exchange between human body and environment based on certain empirical constants and coefficients such as rate of regulatory sweat generation and blood flow from core to the skin, pulmonary ventilation rate, and convective coefficient that are used in the mathematical formulations of comfort prediction models;

- difficulties in precisely determining occupancy factors (such as activity levels, clothing insulation, furniture effects) and shape factors (used in radiation exchange between human body and other surfaces) in field settings;

- field complexity of certain environmental factors (asymmetric radiant fields, significant vertical temperature gradients, complex air movement patterns and related occurrences of draft and turbulency, etc.);

- interference effects of certain personal factors that comfort models may have ignored unjustifiably (differences in age, gender, ethnic and cultural and contextual background, psychological effects, etc.);

- dynamism and variance of both environmental conditions (*ecological valency* in human ecological terms) and occupants' status, activities, and behavior in the field (*ecological potency* in human ecological terms) (see *Appendix C* for an explanation of these terms); and

- possible synergistic interactions between thermal conditions and other relevant surrounding factors (visual and acoustic conditions) and subsequent evaluation of the environment;

There is sufficient evidence in these field studies to indicate that thermal perceptions are affected by recent thermal experiences. To expect one universal standard to cut across different set of people, buildings and climate zones is to belie the findings of past empirical research (Auliciems 1989). A group of thermal comfort researchers believe that existing guidelines and standards in thermal comfort (ASHRAE 1992, ISO 1994) needs to be reevaluated in the light of the discrepancies found between the predicted thermal comfort values based on these standards and *thermal comfort votes* by subjects. They believe that the comfort standards must take into account the adaptive capability of people and should not just be based on a uniform set of thermal comfort parameters. They should, therefore, consider the adaptive control algorithms (Humphreys and Nicol 1995) and the interactions between occupant and environment (both indoor and outdoor, in a climate controlled vs. free running building) in a broader sense. The improved thermal comfort standards can then be used as an architectural design support tool, not just in developed countries where HVAC system are employed widely for climate control but also in developing countries where architects typically must work with passive systems in order to provide thermal comfort.

Many researchers have stated the need for a knowledge-based system to address the inherent deficiencies in the numerical models (Auliciems and de Dear 1978, Baker et al. 1994, Nicol et al. 1995, Mahdavi and Kumar 1996, de Dear and Schiller 1998). Using the results of these field studies is an effort in this direction. The knowledge-based support in TICO has been developed to complement thermal comfort indices derived from the heat balance models of human body discussed in Section 2. Taking advantage of the modular architecture and the dynamic data exchange capability of the SEMPER environment, an active support mechanism has been developed to formulate a richer set of controls strategy with the aim of maximizing occupant satisfaction.

4.2 KNOWLEDGE-BASED SUPPORT

4.2.1 INTRODUCTION

Three strategies have been used to effectively deal with situations where a user can employ the knowledge-based support to further fine-tune the thermal performance of buildings. They are:

4.2.2 INPUT ASSISTANCE AND OUTPUT INTERPRETATION

Thermal comfort terminology, and the variables used in the calculation of thermal comfort indices and the range of values that each variable can take, may sometimes sound arcane to even experienced architects and HVAC designers. There is a strong need to provide assistance to the user at the outset. This mechanism employs lookup methods to retrieve numerical values from the multiple key-value pairs in hash tables.

a) The activity level of humans is typically expressed in $W \cdot m^{-2}$ but most designers would be asked to choose an activity (teaching, office work, sleeping etc.) that will be translated to an appropriate numerical value for carrying out the simulation. *Table 4.1* lists some common activities along with their associated values and, in some cases, relative velocity of air needed to calculate the convective coefficient used in calculations.

b) Thermal comfort is closely linked to the clothing insulation of the entire outfit. The most accurate methods for determining clothing insulation are i) Measurements on

TABLE 4.1: Metabolic rate (W/m^2) as a function of the activity and relative velocity

Activity	Metabolic Rate $[W \cdot m^{-2}]$	Relative Velocity $[m \cdot s^{-1}]$
Sleeping	40	-
Seated, quiet	60	-
Standing, relaxed	70	-
Walking (4.8 km/h)	150	1.3
Cooking	95 …115	0 … 0.2
Washing by hand / ironing	115 … 210	0 … 0.2
Office work	65 … 80	0.05
Teaching	95	-
Digging trenches	300	0.5
Dancing	140 … 255	0.2 … 2.0
Gymnastics	175 … 230	0.5 … 2.0
Tennis	210 … 270	0.5 … 2.0
Basketball	290 … 440	1.0 … 3.0

heated manikins (McCullough and Jones 1984, Olesen and Nielsen 1983) and ii) Measurements on active subjects (Nishi et al. 1975).

For most of the routine engineering work, however, estimates based on tables and equations presented in ASHRAE (ASHRAE 1997) are sufficient. *Table 4.2* lists some of the values used in TICO. There has been a growing concern that upholstered chairs - mostly used in typical office setting - can increase clothing insulation by up to 0.15 clo depending on the contact area (CSAC) between the chair and body (McCullough et al. 1994). The increase in intrinsic insulation (ΔI_{cl}) can be estimated from:

$$\Delta I_{cl} = 7.48 \cdot 10^{-5} CSAC - 0.1 \qquad [\text{clo}] \qquad (4\text{-}1)$$

While taking measurements in a field study, the clothing insulation must be adjusted before using it as an input parameter for TICO. The field study database has applied this correction factor to the value of clo resistance, where applicable.

c) Support is available to explain such technical terms as mean radiant temperature, clothing resistance, and partial vapor pressure that are used to calculate thermal comfort indices. Compliance with international standards (ISO 1994, ASHRAE

TABLE 4.2: Typical Clo Values and Area Factor for Typical Clothing Ensembles

Ensemble Description	Clothing Insulation (I_{cl}) [$W \cdot m^{-2}$]	Clothing Area Factor (f_{cl}) [-]
Walking shorts, short-sleeve shirt	0.36	1.10
Trousers, short-sleeve shirt	0.57	1.15
Trousers, long-sleeve shirt	0.61	1.20
Trousers, long-sleeve shirt, plus suit jacket	0.96	1.23
Trousers, long-sleeve shirt, long sleeve sweater, T-shirt	1.01	1.28
Same as above, plus suit jacket and long underwear bottoms	1.30	1.33
Sweat pants, sweat shirt	0.74	1.19
Long-sleeve pajama top, long pajama trousers, short 3/4 sleeve robe, slippers (no socks)	0.96	1.32
Knee-length skirt, short-sleeve shirt, panty hose, sandals	0.54	1.26
Knee-length skirt, long-sleeve shirt, full-slip, panty hose	0.67	1.29
Knee-length skirt, long-sleeve shirt, half-slip, panty hose, suit jacket	1.04	1.30
Ankle-length skirt, long-sleeve shirt, panty hose, suit jacket	1.10	1.46
Overalls, long-sleeve shirt, T-shirt	0.89	1.27

1992) can be checked with minimal input from the user. This helps ensure that the building meets the thermal comfort guidelines laid out in these standards.

d) Output interpretation of thermal comfort analysis will be available at several resolutions. Explanation of various thermal comfort indices and the significance of the results in terms of the acceptability (percentage of people likely to be satisfied or dissatisfied) of the thermal environment will be available. A more elaborate analysis will involve checking:

- personal and environmental variables to make sure they are within the bounds of the specified standards.
- that total percentage of people dissatisfied with the general thermal environment does not exceed 20%.

4.2.3 A FIELD STUDY BASED EVALUATIVE APPROACH

4.2.3.1 Introduction

This approach fine tunes the results derived from the classical thermal comfort algorithms based on the numerous field studies that have been conducted over the past 15 years. The range of the modified thermal comfort indices predicted by this approach is limited to the availability of field study data in electronic format. Currently, the computational module works in tandem with a database of field studies made available under ASHRAE RP-884 (de Dear 1998). *Figure 4-1* shows the evaluative approach in its conceptual form. Steps shown in the top rectangle were part of the RP-884 project whereas the bottom rectangle shows what was implemented in TICO.

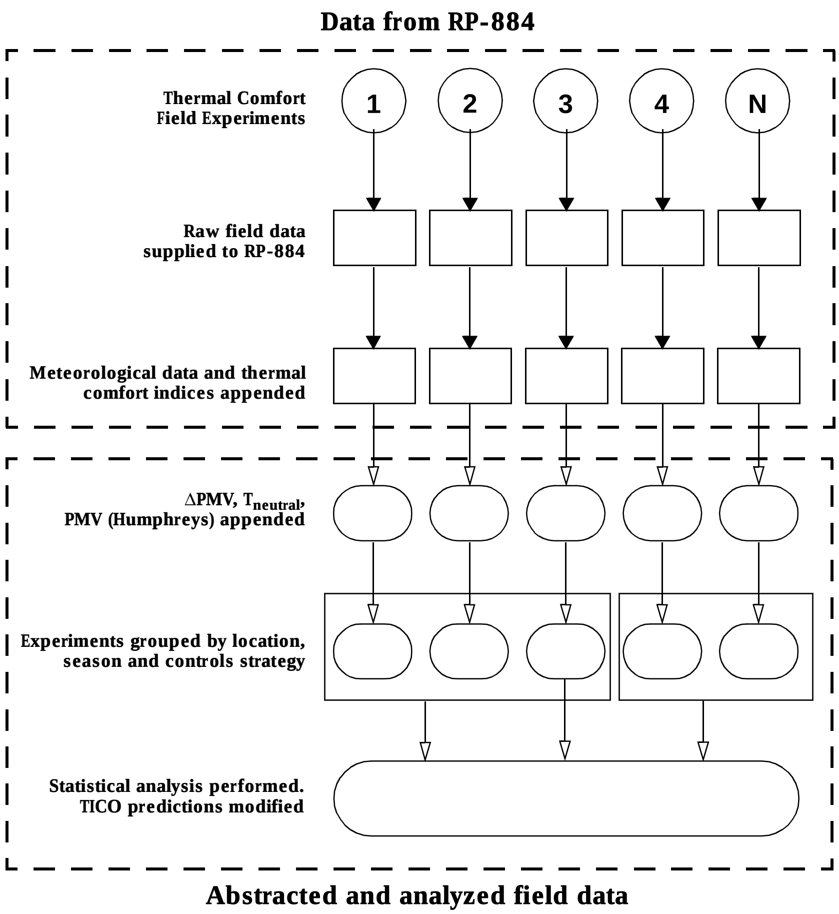


Figure 4-1: Conceptual sketch of the pre-processing of data in the evaluative approach

The strategy to find one or more suitable cases from the search domain is outlined below. It is to be noted that because of the limited number of field studies currently available in the database, the search mechanism employed during the analysis is of critical importance. Most of the work, therefore, went into the pre-processing of the database and a strategy has been developed that offers "expert" advice to the users. Furthermore, to help the users judge the quality of the recommendations, a rating criteria has been evolved. The advantage of such a system is that it is the user who ultimately decides to either accept or reject the advice. The key variables involved in the analysis are:

a) Climate/Geographical Location: Obviously, the location of the building is one of the key criteria used in this analysis. Based on the information gathered from the weather file, the design will be grouped into one of the following nine climatic regions of the world. The same classification was used by thermal comfort researchers to compile the field study database. It is, therefore, imperative that one uses the same classification to avoid any discrepancy while mapping the climate associated with cities. If the climatic region for a city is not listed, the user has the option of specifying one of the climatic regions directly or relying on the heuristic of the module to come up with an approximate match. The climatic regions with examples are listed below:

- *Continental Subarctic* (Montreal, Helsinki, etc.)
- *Desert* (Las Vegas, Cairo, Karachi, etc.)
- *Humid Midlatitude* (Beijing, Moscow, Ottawa, etc.)
- *Humid Subtropical* (Houston, Sydney, Dhaka, etc.)
- *Mediterranean* (Athens, San Francisco, Rome, etc.)
- *Semi-arid Midlatitude or Semi-desert* (Peshawar)
- *Temperature Marine or West Coast Marine* (Vancouver, London, Melbourne, etc.)
- *Tropical Savanna* (Bangkok, Delhi, Sao Paolo, etc.)
- *Wet Equatorial* (Jakarta, Singapore, Manila, Colombo, etc.)

b) Environmental Control System: There is a distinct correlation between the level of thermal comfort desired by occupants in a building and the controls system in place for regulating the environmental parameters inside a building. Field studies have thus been classified according to:

- Active Controls
- Passive Controls
- A combination of active and passive controls

c) **Season**: Hourly values of environmental parameters, together with thermal comfort indices for each zone can be further divided by season to facilitate a more detailed season-specific analysis. This option is provided because of the dependence of thermal comfort perception on the prevailing season. The three seasons used in this classification are:

- Summer
- Winter
- Swing (Spring, Fall)

4.2.3.2 Data Abstraction from Field Studies

The field studies made available under RP-884 store large amount of data, not all of which is directly relevant for the analysis. The field studies database was organized under 80 different fields which can broadly be classified under the following headings:

- Basic identifiers (subjects, age, sex, frequency of observation, year, etc.)
- Thermal questionnaire (thermal and air movement preference, activity level, clothing, etc.)
- Indoor climate (air and globe temperature, air speed and turbulence)
- Environmental and personal parameters (air and mean radiant temperature, air velocity, relative humidity, clothing and activity level)
- Calculated indices (Operative Temperature, Standard Effective Temperature, PMV, PPD, TSENS, DISC, etc.)

- Personal environmental control options - both active and passive such as ability to open windows, internal doors, set thermostat, control blinds, and local fans.

- Outdoor meteorological data (outdoor air temperature, relative humidity, etc. in morning, afternoon and evening)

All fields were checked to see if they had statistically significant sample sizes before being considered for detailed analysis. For instance, under *personal environmental control* category, there were some fields that could have been extremely useful in analyzing their effect on the indoor thermal environment. However, the absence of sufficient data points made it impossible to select them for further analysis. After careful consideration, key parameters that affect thermal comfort and energy performance were short-listed from the original list of 80 variables and are shown in *Table 4.3*. Three variables DIFF (ASH - PMV) - also referred to as ΔPMV, $T_{neutral}$ (Humphreys), and PMV (Humphreys) were not originally in the database and were calculated for each of the 46 field studies during pre-processing of data. The sequence of steps that was followed is:

- The six factors affecting thermal comfort, outdoor temperature, ASH or people's thermal sensation on the 7-point ASHRAE scale, PMV, DIFF (ASH - PMV) or difference between the observed value and predicted value, and PPD are selected. Critical information pertaining to the climate, ventilation and season type and the year in which the study was conducted is also selected from the list of variables for detailed reporting purposes.

- For each of the 46 field studies, mean values of all the identified variables are calculated so that each study ends up with one set of average values (the first data row in *Table 4.3*). Total number of subjects and total number of data points are stored for each study (fifth row in *Table 4.3*) to be used for finding out the statistical significance of experiments.

- The maximum and minimum values and the standard deviation of the sample set for each of the variables affecting thermal comfort are also calculated and stored (second, third and fourth row of the *Table 4.3*).

- One noteworthy point about the entire analysis is the assumption of a normal distribution of thermal sensation votes (ASH), which is also the basis of the PMV-PPD model.

TABLE 4.3: Matrix following data abstraction for each field study

ASHRAE Scale (empirical)	PMV (calculated)	PMV (Humphreys)	DIFF(ASHRAE-PMV)	PPD	Air Temperature	MRT	Air Velocity	Relative Humidity	Outdoor Air Temperature	$T_{neutral}$ (Humphreys)	
0.66	1.33	0.80	-0.67	0.47 0.42 (cal)	29.41	29.79	0.22	73.52	27.38	25.45	Avg.
N/A[a]	N/A	N/A	N/A	N/A	26.00	26.83	0.05	57.92	26.94	N/A	Min.
N/A	N/A	N/A	N/A	N/A	31.90	31.92	0.58	97.83	27.39	N/A	Max.
N/A	N/A	N/A	N/A	N/A	1.23	1.19	0.12	6.64	0.07	N/A	Std. Dev.

Climate	System Type	Researcher	City	Year	Season	Data pts.
Wet Equatorial	Naturally Ventilated	de Dear et al.	Singapore	1991	Summer	583

a. The min., max., and standard deviation row were used for calculating "reliability index" and hence calculated for thermal comfort variables and not for any performance indices

- A new index, ΔPMV (ASH - PMV) is derived instead of PPD from field data. The plot in *Figure 4-2* shows the discrepancies between observed and predicted values. If this plot is top heavy (ΔPMV is positive), then it is a clear indication that majority of the population is warmer (or not as cold depending on the actual thermal sensation values) than what is currently being predicted by Fanger’s PMV. By the same token, if the plot is bottom-heavy (ΔPMV is negative), the average thermal sensation of the population is colder (or not as warm depending on the actual thermal sensation values) in comparison to the values predicted by Fanger’s model. If either of these situations is true, as happens in 39 out of 46 field studies, a clear inference can be drawn from the field studies, and a corresponding correction factor can be applied to the computed value of PMV. In the remaining 7 cases, there is no clear indication since almost half the population feels warmer and the other half feels colder than what is being predicted by the model. Instead of modifying the predicted PMV in such a case, no correction factor is applied. *Figure 4-3* shows the discrepancy between observed and predicted values using ΔPMV for benchmarking all the field studies. It also shows that the discrepancies are more pronounced in free running buildings (8% as compared to 16%) and the PMV model seem to exaggerate thermal discomfort on the warmer side.

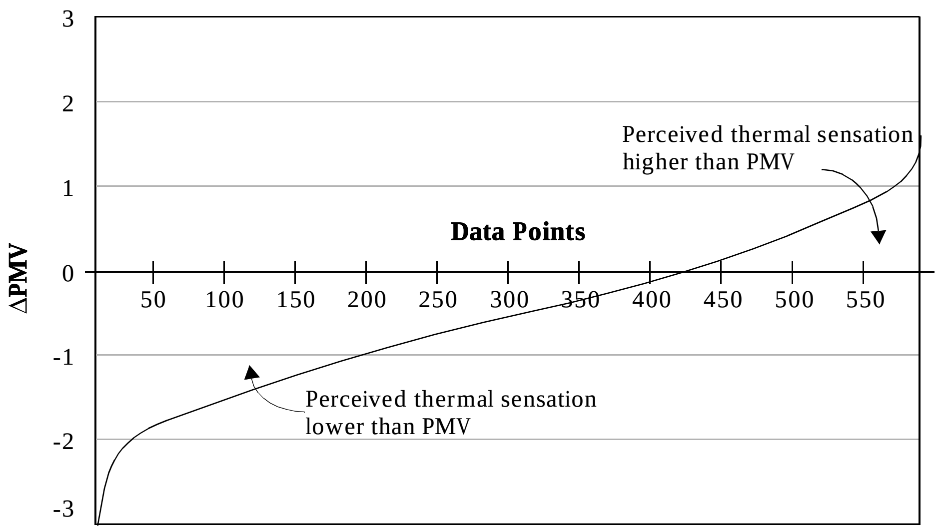
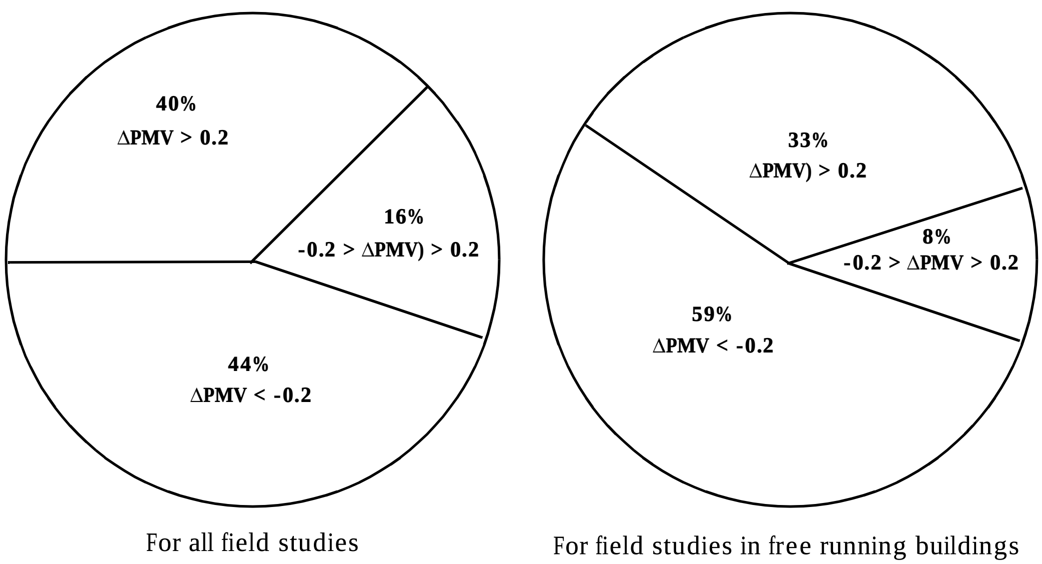


Figure 4-2: ΔPMV plotted for field study shown in *Table 4.3*



For all field studies

For field studies in free running buildings

Figure 4-3: Range of discrepancy between predicted and observed values

There is evidence that people's perception of their thermal environment does vary by season. Therefore, in order to allow for a detailed comparison, data obtained from TICO is encapsulated based on the season in which the selected field studies were conducted.

The following assumptions are made while performing this analysis:

- Summer, winter and swing months are noted for the design situation and depending on the hemisphere, field studies are selected accordingly.
- Hourly values of the variables from 8:00 AM to 6:00 PM are taken into account so that night setback effects can be ignored. It is a reasonable assumption because a majority of the field studies would have been conducted within this time period.

4.2.3.3 Methodology

The methodology adopted is outlined below:

a) For a specific design situation, an hourly simulation is run to calculate thermal comfort indices (PMV, SET*, TSENS, DISC). Consequently, for example, an average value of PMV together with the mean of environmental and meteorological parameters are, either inherited from NODEM and other SEMPER modules (air temperature, air velocity) or calculated inside TICO (mean radiant temperature). For analysis purposes, the mean values of the parameters are calculated based on either the number of occupancy hours or a 24 hour period.

b) An initial screening is performed using climate and control types to reduce the sample size of the field studies in the database. The premise is that both thermal comfort and energy usage are closely linked to these two variables and at a minimum, a match is needed against them before proceeding to conduct a more complex analysis.

c) From this reduced pool of field studies, a compensation factor ΔPMV is derived based on the range specified for individual thermal comfort variables. A *reliability index* is associated with each ΔPMV term by following the matrix shown in *Table 4.4 on page 39*. The analysis behind the evolution of this rating is described below.

Table 4.4 lays out the criteria for deriving the *reliability index* of the expert advice. After a match has been found based on the control type and the climate in which the simulated building is located, the four environmental variables under current design conditions are compared against the corresponding value of the variable for the field study and points are allocated that can range (in case of air temperature) from a maximum of 35 to a minimum of 3. Thus, the range of rating for any advice can vary from a maximum of 100 (best) to a minimum of 15 (worst).

TABLE 4.4: Reliability Index for the "expert" advice derived from field study data

	Within ± 1 Standard Deviation	Within Min/Max value	No restriction
Air Temperature	35	15	3
MRT	25	10	3
Air Velocity	25	12	4
Relative Humidity	15	8	5
Total	100	45	15

This reliability index provides a quantitative framework to adjust the value of thermal comfort indices (PMV, in this case). In *Equation 4-2*, ΔPMV is the adjustment resulting from the analysis, which should be made to the value of PMV calculated in TICO. W_1, W_2, etc. are the *reliability indices* and ΔPMV_1 and ΔPMV_2 are the compensation factors derived from the matching field studies. $PMV_{modified}$ can be interpreted as a term that has accounted for the discrepancy found in observed and predicted values.

$$\Delta PMV = \frac{W_1 \times \Delta PMV_1 + W_2 \times \Delta PMV_2 + \ldots + W_n \times \Delta PMV_n}{\sum W} \qquad (4\text{-}2)$$

$$PMV_{modified} = PMV_{simulated} + \Delta PMV \qquad (4\text{-}3)$$

This adjusted value ($PMV_{modified}$) is used as the starting point for providing feedback to NODEM so that changes at the system level (in conjunction with BACH and HVAC module) or design level (SEMPER) can be made. The knowledge-based system framework developed in this section is implemented in TICO and the results are illustrated via two examples in Chapter 5.

4.3 ACTIVE DESIGN SUPPORT IN TICO

4.3.1 INTRODUCTION

The results of this analysis to modify PMV can now be used to:

- design an indoor thermal environment that satisfies more people and is energy-efficient as well;

- provide better and optimized controls for the indoor thermal environment that will result in a still higher satisfaction level for the occupants.

The accomplishment of these two objectives would be simpler if, instead of starting with a list of values of key variables and then calculating *PMV*, one could reverse the process by starting with a pre-defined *PMV* value depending on the design context and performing a parametric analysis. However, the non-linear nature of *Equation 2-5 on page 14* makes it infeasible to formulate a simple mathematical relationship between air temperature and PMV, or air velocity and PMV, for example, that can be captured in an equation. An approach that goes beyond the one adopted by conventional simulation tools is required—one that will reverse the traditional design process. A new methodology can be developed, which entails recognizing performance (PMV or PPD) and design variables (air temperature, air velocity etc.) at the outset and evolving a quantitative framework to implement the active support algorithm.

4.3.2 Bi-Directional Functionality in TICO

Past research has established the concept of a bi-directional simulation environment to facilitate the interactive and simultaneous modification of properties and the observation of changes in various building design and performance variables (Mahdavi 1993, Mahdavi and Berberidou-Kallivoka 1993a). In a bi-directional simulation environment, designers modify and observe both *design and performance* variables at different levels of abstraction. This is contrasted with the conventional simulation tools, which are mono-directional in that they transform the relevant design and context attributes into performance attributes, but do not allow for design attributes to be generated or modified based on the desired performance attributes. The bi-directional approach can increase the effectiveness of computational design support environments in at least two ways: a) by reducing the number of parametric variations of design variables a designer may need to explore as the performance goal is defined at the outset, and b) by enhancing the designer's understanding of the complex and dynamic interactions between various design and performance variables.

The transformation of performance attributes into specific design attributes cannot be formalized in deterministic terms because there are multiple sets of design variables that would map to a desired value of performance variables. This remains the biggest challenge in developing a bi-directional analysis tool and has been labeled as the ambiguity problem (Mahdavi and Berberidou-Kallivoka 1994). In most design problems, however, the design variables are constrained by building codes, contextual parameters, technological limitations, and designers' preferences. A bi-directional analysis tool incorporating such constraints can support performance responsive design generation and modification.

As noted earlier, since the performance-to-design mapping process is an ambiguous one, the same performance (e.g. optimizing PMV or minimizing PPD) can be achieved by passive design configurations (window dimensions/properties, ventilation or shading characteristics of design, varying thermal mass and insulation, etc.) or evolving a control strategy for HVAC systems (controlling the supply air temperature or regulating the temperature of radiant panels, incorporating enthalpy controls, etc.). As a result, the actual implementation of a bi-directional inference tool requires a clear decision-making process that can be applied unambiguously at any stage of design. Instead of relying completely on a preference mechanism, a hybrid approach (both preference and heuristic based) that involves the formalization of various external or internal constraints and preferences (such as code and standard requirements or results of field studies) is implemented here to achieve the desired performance.

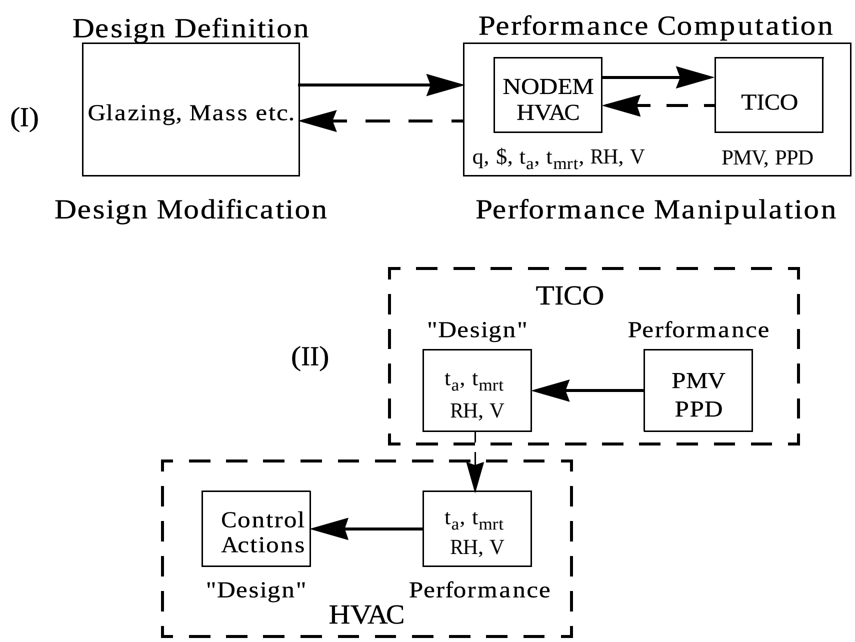


Figure 4-4: Two Modes of Bi-directional Support

Two modes of bi-directional support have been implemented. In the first case, the user can specify her performance requirements by requesting SEMPER to a) maximize thermal satisfaction and/or b) minimize energy use or minimize total energy cost in the current design. In such a situation, the thermal suite of applications in SEMPER takes necessary actions and suggests design changes to the user, which would help in achieving the performance requirements of the design. An example that shows how NODEM, BACH and TICO work together to maximize thermal satisfaction is shown in *section 5.3.2 on page 58*.

In the second case, the inherent intelligence embedded in TICO is used to guide the HVAC module to achieve the environmental conditions that would satisfy the performance objectives of the design. The bi-directional process, in this case, can be viewed as a two-step process. In the first step, a target value of PMV - we call it the first-order performance variable - is either specified by the designer or suggested by TICO after analyzing field study data. The environmental parameters such as air temperature, mean radiant temperature, relative humidity, and air velocity, which can all be theoretically controlled by HVAC systems are the design variables that can be modified to bring about the desired changes in the performance variable. A methodology outlined below, which relies on the knowledge ingrained in TICO is used to suggest changes in the design variables that will bring the performance variable closer to its final value. In the second step, the design variable, say air temperature, becomes the performance variable that can be modified by the HVAC module. The HVAC module can bring about this change by taking appropriate controls actions such as, changing the chilled water temperature, modifying the economizer settings or changing the speed and volume of supply air in the distribution system. The first stage of this bi-directional strategy has been implemented in TICO and the second step will become functional once the HVAC module is integrated with the SEMPER framework. The concept is illustrated via an example in *section 5.3.1 on page 55*.

The first stage of the bi-directional thermal comfort inference mechanism involves:

1. Identifying *performance variables* such as *PMV* and *PPD*, and defining the objective function such as *Min* (PMV) at TICO level that would drive the optimization process.
   Predicted Mean Vote (PMV): Hourly values of PMV calculated in TICO is used to arrive at the initial value of PMV. Subsequently, PMV in a space is assessed by taking a mean value of the hourly values over an entire season or year. For obvious reasons, hours coinciding with the occupancy schedule have been used to calculate the mean value of PMV. Optimizing PMV is the major goal of the bi-directional analysis. A user can specify an acceptable range for PMV in which case the bi-directional

inference mechanism makes sure that the value of PMV remains in the specified range by constraining the values of the design variables.

2. Identify relevant *design variables,* such as air temperature, mean radiant temperature, and air velocity etc. and then assigning boundary conditions and default values to them.

   For each of the design variables, an allowable range is set by defining the minimum and maximum values, and an ordered set of discrete values within the allowable range is determined using a fixed increment value. In the current implementation, four design variables have been defined. *Table 4.5* identifies the design variables along with their boundary conditions and default values in deriving the preference attributes for them. In the case of air temperature, the minimum, maximum and default values are 18°C, 30°C and 24°C respectively as shown in *Table 4.5*. However, the user has the flexibility of setting one or all three values for all the design variables.

TABLE 4.5: Design variables with their min, max and default values

Design Variables	Minimum	Maximum	Default	Increment
Air Temperature	18°C	30°C	24°C	0.6°C
MRT	18°C	30°C	24°C	0.6°C
Air Velocity	0	$0.5\ m \cdot s^{-1}$	$0.15\ m \cdot s^{-1}$	$0.02\ m \cdot s^{-1}$
Relative Humidity	20%	80%	50%	2%
Activity	N/A	N/A	$60\ W \cdot m^{-2}$	N/A
Clothing	N/A	N/A	$0.155\ m^2 \cdot K \cdot W^{-1}$	N/A

3. Derive the *normalized distance (D)* attribute for each of the variables identified above. The normalized distance attribute of the design variables is proportional to the difference between the current and default value. *Figure 4-5* and *4-6* shows this relationship between air or mean radiant temperature and air velocity respectively. For example, the normalized distance for an air temperature of 19.5°C is 0.6.

4. Derive the *effectiveness (E)* attribute for each design variable. Under the *bi-directional* approach, the ability to bring about a change in PMV is termed as the *effectiveness* of a design variable. The concept is illustrated by *Figure 4-7* and 4-8. To derive *E*, an incremental change is made in the variable and the change in the value of the per-

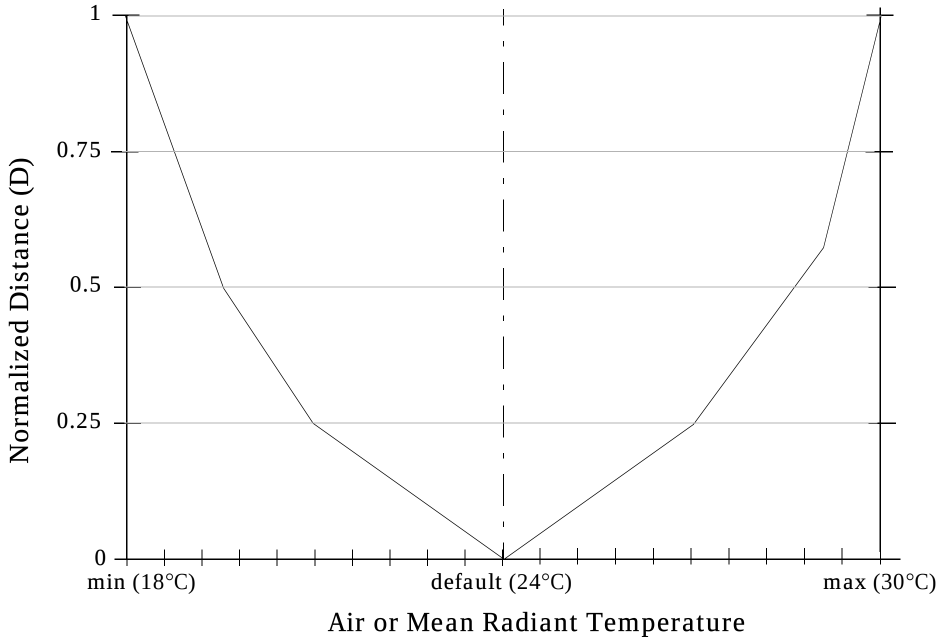


Figure 4-5: Illustration showing the derivation of normalized distance attribute

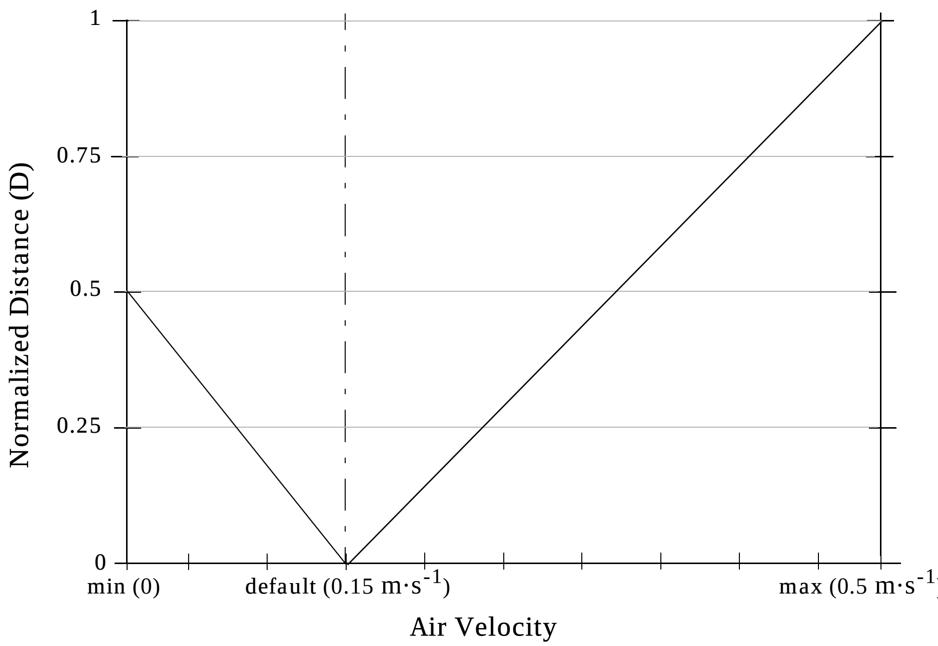


Figure 4-6: Illustration showing the derivation of normalized distance attribute

formance variable is recorded. The increment for each design variable was shown in *Table 4.5*. For example, *E* for air temperature is given by:

$$E_t = \frac{PMV_{t_i} - PMV_{t_{(i+\Delta t)}}}{\Delta t} \tag{4-4}$$

A more descriptive explanation of the design variables together with their *effectiveness* attribute is given below:

Air Temperature: The air temperature within a space is used by TICO for the calculation of various thermal comfort indices. The initial value is obtained on an hourly basis via NODEM and may be defined over a domain of one or more spaces. Air temperature can always function as a design variable to achieve desired performance. *Figure 4-7* shows the relative rate of change of PMV with respect to air temperature. For instance, for a person doing normal sedentary work, wearing clothes with a clo value of 1.0, in an air velocity of 0.1 $m \cdot s^{-1}$, each °C change in air temperature is going to change the PMV by 0.22 units.

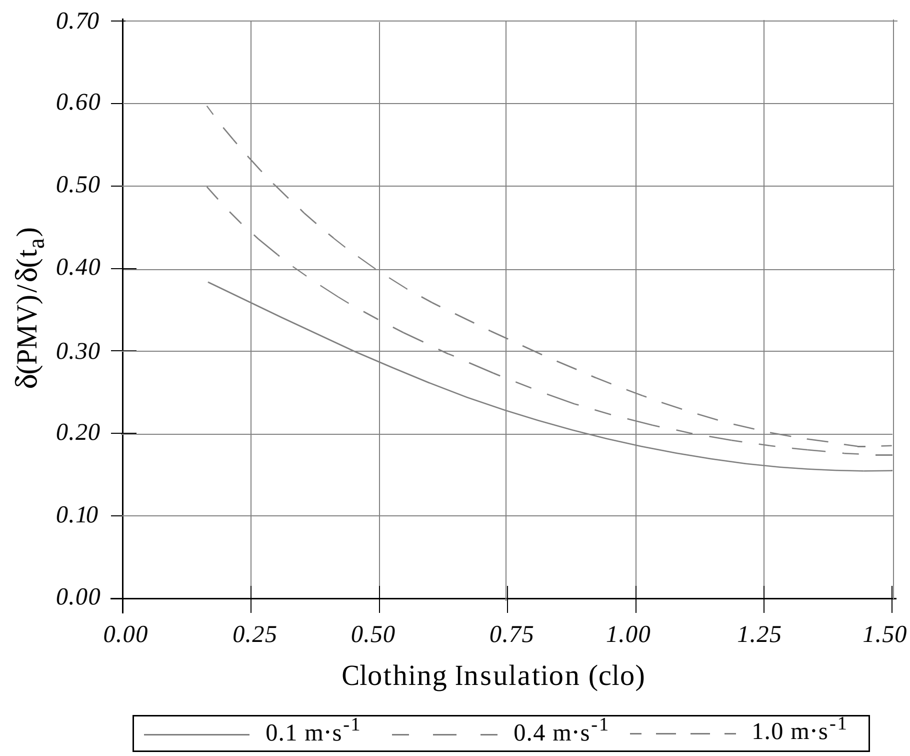


Figure 4-7: Rate of change of PMV as a function of air temperature for different air velocities

Mean Radiant Temperature: The surface temperature of various orthogonal surfaces including ceiling, floor, walls and windows together with their spatial layout in a space is used to calculate the initial mean radiant temperature (Mahdavi and Mathew 1993b). The geometrical attributes and hourly values of surface temperatures are transmitted to TICO by NODEM. MRT's influence as a design variable would be greater when the building is running in active mode especially if there are radiant panels or spot heaters to condition people, not the entire occupied space. *Air Velocity:* The initial value is obtained on an hourly basis via BACH and is defined over a domain of one or more spaces. Air velocity can be changed by either manually operating the windows (passive mode) or controlling fan and damper settings (active mode). *Figure 4-8* shows the relative rate of change of PMV with respect to air velocity. For a person doing normal sedentary work, wearing clothes with a clo value of 1.0 in an environment with air and mean radiant temperature of 23°C, each 0.1 $m \cdot s^{-1}$ change in air velocity is going to change the PMV by 0.05 units.

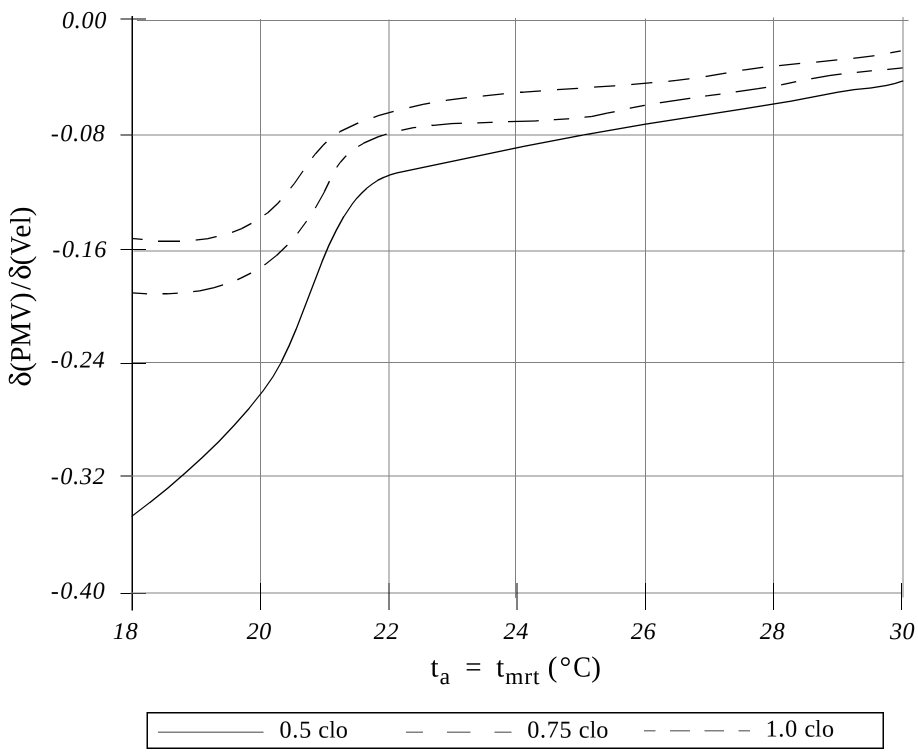


Figure 4-8: Rate of change of PMV as a function of air velocity for different clo values

Relative Humidity: If the environmental control system has humdification and dehumidification capability, relative humidity can function as a design variable. Although not as critical a factor as the other three discussed above in evaluating thermal comfort, it can have a moderate effect on PMV and a significant effect on total energy use in a facility. The relative humidity is the least effective of the four environmental parameters in terms of its ability to modify PMV. The relative humidity is the least effective of the four environmental parameters in terms of its ability to modify PMV. Approximately, for every 10% change in relative humidity, PMV changes by 0.01 units in a typical office environment.

5. Derive a *relative normalized distance* (D_{rel}) attribute for each of the four design variables. To calculate $D_{rel,\,i}$, the *normalized distance* attribute for each variable $D_1 \ldots D_n$ (already calculated using the stepped curve function derived earlier) will be used. The $D_{rel,\,i}$ for any variable is then given by:

$$D_{rel,\,i} = \frac{D_i}{Max(D_1 \ldots D_n)} \tag{4-5}$$

6. Derive a *relative effectiveness* (E_{rel}) attribute for each of the four design variables. $E_{rel,\,i}$ (relative effectiveness of nth design variable) is derived using the individual effectiveness (E) of design variables calculated in step 4. For any design variable, it can now be calculated using *Equation 4-6*.

$$E_{rel,\,i} = \frac{E_i}{Max(E_1 \ldots E_n)} \tag{4-6}$$

7. Calculate the *preference* (P) index for each of the variables at each design stage as shown in *Equation 4-7* and store the design variables in order of decreasing preference index together with their current values in a list.

$$P = w_E \times E_{rel} + w_D \times D_{rel} \tag{4-7}$$

E_{rel} and D_{rel} for each of the design variables have been defined in step 5 and 6 respectively. w_E and w_D are the corresponding weighting factors for these two attributes. For the purpose of the current implementation, a value of $w_E = w_D = 0.5$ has been used, which means that P must lie between 0 and 1.

8. In the case of an active design, the design variable with the highest preference index is passed to the HVAC module. In a passive design situation, the ordered list of design variables is passed to NODEM. The design variable with the highest preference index will be modified by adding or subtracting the increment derived from *Table 4.5 on page 43* and calculated in step 3. If design limitation does not allow NODEM to bring about the change using the design variable with the highest prefer-

ence index then the next design variable in the sorted list will be selected. This process will go on till NODEM modifies one of the design variables or a better performance cannot be achieved under the current set of design conditions.

9. Iterate through steps 3-8 till the objective function is satisfied or a better performance cannot be achieved.

5 Illustrative Case Studies

5.1 INTRODUCTION

In this section, two scenarios are presented that illustrate the field-study based evaluative capabilities and bi-directional inference mechanisms of TICO respectively:

- Under the first scenario, two examples are presented. In the first example, TICO suggests a modification in the value of simulated PMV in an "active" building by culling contextual knowledge from the field studies. In the second example, the same procedure is repeated for a passive building and Fanger's PMV is modified by analyzing field data using the methodology developed in the previous chapter.
- Next, two bi-directional examples are presented in *Section 5.3*. In the first instance, the first stage in the two-stage optimization process is performed by TICO, which then requests the HVAC module to make the corresponding change. In the second instance, a bi-directional inference mechanism at the SEMPER level involving TICO, NODEM and BACH is illustrated.

5.2 IMPLEMENTATION OF FIELD STUDY BASED EVALUATIVE APPROACH

5.2.1 CASE 1

The sequence of steps starting from design description to specification of search criteria to the derivation of weighting factor for modifying PMV is outlined below:

1. *Figure 5-1* shows the plan of the building along with the space and grid information. As NODEM iterates through the spaces, it calls TICO, passing the geometric

attributes of spaces with thermal parameters as arguments. TICO then calculates mean radiant temperature and PMV data for each space. *Table 5.1* shows the detailed results for each cell in the building.

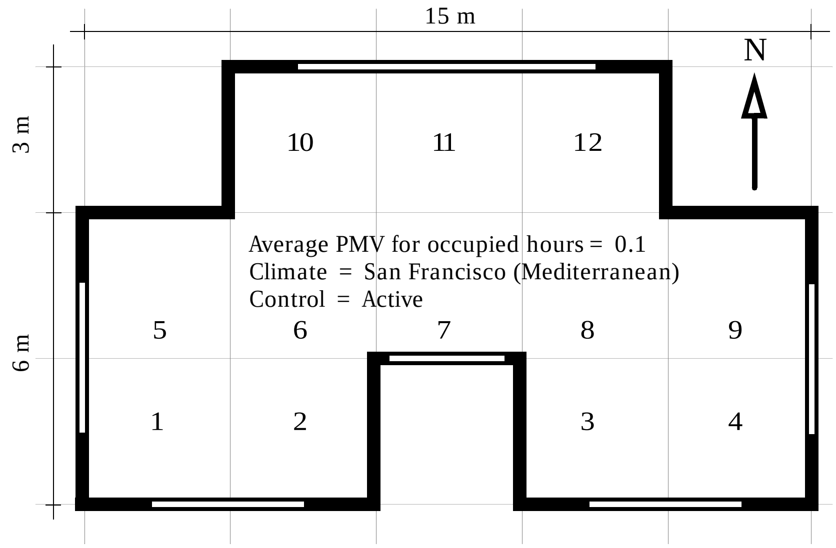


Figure 5-1: Schematic design for a building in San Francisco

TABLE 5.1: Average PMV, air and mean radiant temperature data for each space

Cell	Average air temperature for occupied hours	Average MRT for occupied hours	Average PMV for occupied hours
1	25.6	25.5	0.2
2	25.8	25.2	0.19
3	25.8	25.8	0.24
4	25.6	12.8	-1.08
5	25.8	25.5	0.21
6	26.0	26.2	0.31
7	25.9	25.8	0.25
8	26.0	26.1	0.30
9	25.3	23.1	-0.07
10	25.9	24.6	0.16
11	25.8	25.5	0.22
12	25.9	25.7	0.24

2. Based on the methodology evolved in *section 4.2.3.3 on page 38*, NODEM communicates the climatic region and the environmental control system type for the current design to TICO. They are:

- Climatic region: San Francisco (Mediterranean)
- Environmental Control System: HVAC system (active)

3. To perform the first step in field study based analysis, the two parameters (climate and controls type) mentioned above are used to perform a search on the database. A selection is made from the set of field studies that satisfy the search criteria. In this case, six matching case-studies are found and their summary information is displayed below in *Table 5.2*.

TABLE 5.2: Field studies matching the climate and ventilation type specified in the current design

City	Climate	Control	Season	Year	Researcher	# of Sub.	# of Pts.
San Francisco	Mediterra-nean	Active	Summer	1988	Schiller et al.	151	673
San Francisco	Mediterra-nean	Active	Summer	1988	Schiller et al.	185	918
San Ramon	Mediterra-nean	Active	Summer	1994	Benton et al.	39	285
San Ramon	Mediterra-nean	Active	Summer	1994	Benton et al.	27	96
Auburn	Mediterra-nean	Active	Summer	1993	Benton et al.	27	128
Antioch	Mediterra-nean	Active	Summer	1995	Benton et al.	30	111

4. Once the relevant field studies have been identified, the discrepancy between Fanger's predicted PMV and thermal sensation (ΔPMV) experienced by people is recorded. *Table 5.3* shows the environmental parameters recorded in field studies and compares it with the values in the current design situation. The reliability index for applying a ΔPMV term to Fanger's PMV is shown in the 3rd column of *Table 5.3* for the six field studies. Since all six point to a positive adjustment to the predicted PMV, an adjustment is made based on *Equation 4-2 on page 39*.

5. This results in a weighted ΔPMV of 0.46 and the simulated PMV value (0.1) must be adjusted by this factor to take into account the results from the six field studies as shown in *Figure 5-2*. With the derivation of the weighted ΔPMV term, the field study based analysis and subsequent modification of PMV is complete.

TABLE 5.3: Adjustment factor for PMV and the associated reliability indices

Comparison	Averages	Variance (Min, Max, SD)	Reliability Index
Design values	T_{air} = 25.6°C MRT = 25.5°C RH = 54% PMV = 0.1	Not Required	Base Case
Field Study 1	T_{air} = 23.1°C MRT = 23.2°C RH = 45%	T_{air} = 22.2°C, 23.8°C, 0.3°C MRT = 22.4°C, 23.9°C, 0.3°C RH = 41%, 48%, 1.6%, ΔPMV = 0.7	30
Field Study 2	T_{air} = 22.0°C MRT = 22.1°C RH = 74%	T_{air} = 20.3°C, 23.3°C, 0.7°C MRT = 20.0°C, 23.5°C, 0.7°C RH = 43%, 55%, 2.5%, ΔPMV = 0.47	45
Field Study 3	T_{air} = 22.7°C MRT = 22.9°C RH = 50%	T_{air} = 21.1°C, 23.6°C, 0.5°C MRT = 21.27°C, 23.87°C, 0.5°C RH = 45%, 56%, 2.7%, ΔPMV = 0.56	61
Field Study 4	T_{air} = 22.0°C MRT = 22.1°C RH = 30%	T_{air} = 19.1°C, 25.6°C, 0.9°C MRT = 16.6°C, 24.8°C, 0.9°C RH = 18%, 41%,5.7%, ΔPMV = 0.34	70
Field Study 5	T_{air} = 22.7°C MRT = 22.7°C RH = 35%	T_{air} = 17.4°C, 29.8°C, 1.2°C MRT = N/A RH = 19%, 57%, 7.4%, ΔPMV = 0.44	73
Field Study 6	T_{air} = 23.0°C MRT = 23.3°C RH = 62%	T_{air} = 20.1°C, 27.6°C, 1.0°C MRT = 20.3°C, 27.6°C, 0.9°C RH = 49%, 78%, 5.14%, ΔPMV = 0.42	73

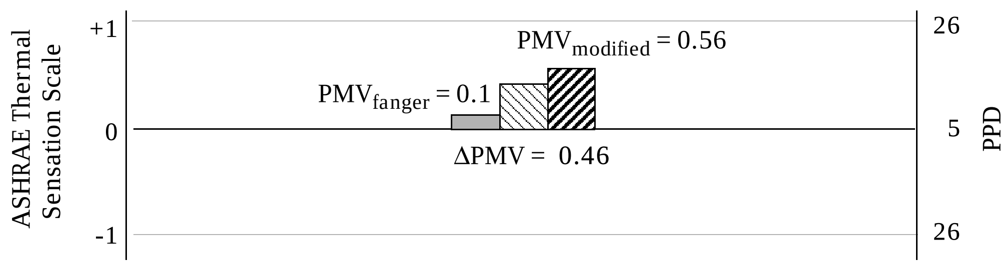


Figure 5-2: Modifying Fanger's PMV with field studies findings to maximize satisfaction

5.2.2 CASE 2

Just as in case 1, the sequence of steps for modifying PMV based on matching field studies is shown below:

1. *Figure 5-3* shows the schematic design of a building along with the space and grid information. NODEM interacts with TICO by passing the geometric attributes of spaces with thermal parameters as arguments. As NODEM iterates through the spaces, it calls TICO and the resulting grid of mean radiant temperature and PMV is

shown in *Figure 5-3*. This capability to simulate mean radiant temperature and thermal comfort values for each cell in a building can help in devising a better control strategy, which is one of the goals of this research.

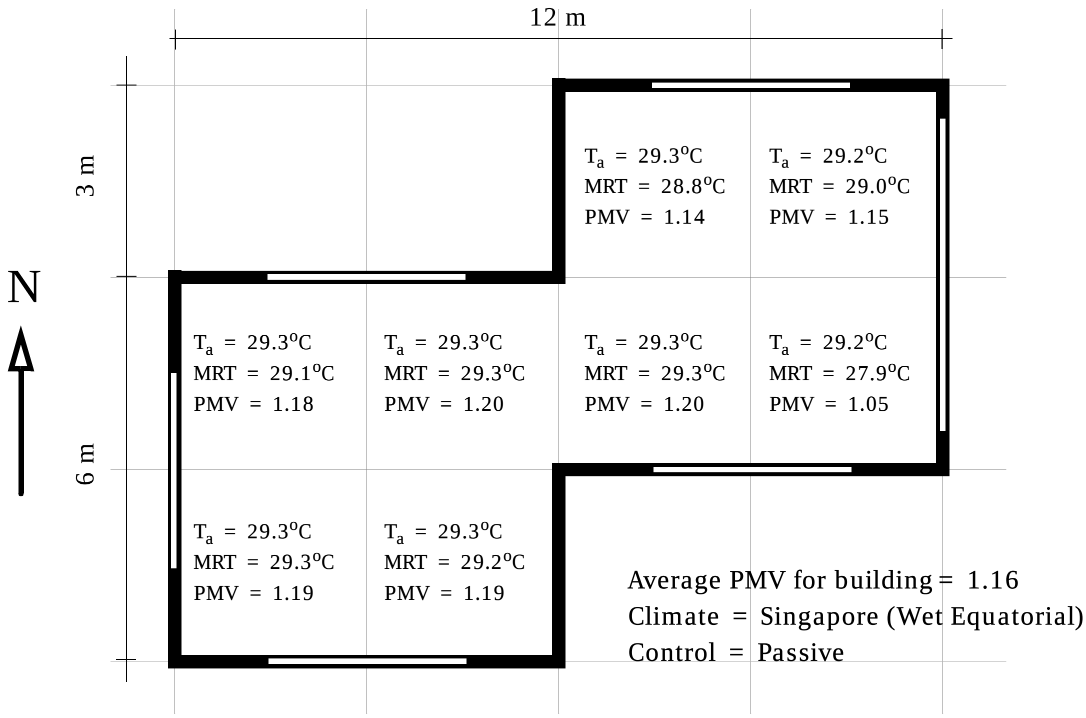


Figure 5-3: Results of running TICO on a building in Singapore in tandem with NODEM

2. Based on the methodology evolved in *section 4.2.3.3 on page 38*, NODEM communicates the climatic region and the environmental control system type for the current design to TICO. In this case, they are:

   - Climatic region: Singapore (Wet Equatorial)
   - Environmental Control System: Natural Ventilation (passive)

3. The two parameters identified above are passed on as arguments to the TICO module for field study evaluation. It performs a search on the database and selects the studies that satisfy the search criteria. In this case, two matching field studies are found and their summary information is displayed below in *Table 5.4*.

4. Once the relevant field studies have been identified, the discrepancy between Fanger's predicted PMV and thermal sensation (ΔPMV) experienced by people is recorded. *Table 5.5* shows the environmental parameters recorded in field studies

TABLE 5.4: Field studies matching the climate and ventilation type specified in the current design

City	Climate	Control	Season	Year	Researcher	# of Sub.	# of Pts.
Jakarta	Wet Equatorial	Passive	Summer	1995	Karyono	97	97
Singapore	Wet Equatorial	Passive	Summer	1991	de Dear	583	583

and compares it with the values in the current design situation. The reliability index developed in *Table 4.4 on page 39* for applying a ΔPMV term to Fanger's PMV, is shown in the 3rd column of *Table 5.5* for the two field studies. If all the short-listed field studies have the same ΔPMV sign, as is the case above (both point to a negative adjustment to the simulated PMV), an adjustment is made based on *Equation 4-2 on page 39*.

TABLE 5.5: Adjustment factor for PMV and the associated reliability indices

Comparison	Averages	Variance (Min, Max, SD)	Reliability Index
Design values	T_{air} = 29.3°C MRT = 29.0°C RH = 81% V_{air} = 0.1 $m \cdot s^{-1}$ PMV = 1.16	Not Required	Base Case
Field Study 1	T_{air} = 30.3°C MRT = 30.3°C RH = 72%	T_{air} = 28°C, 32°C, 1.0°C MRT = N/A RH = 69%, 79%, 3.15% ΔPMV = -0.52	90
Field Study 2	T_{air} = 29.4°C MRT = 29.8°C RH = 74%	T_{air} = 26°C, 31.9°C, 1.2°C MRT = 26.8°C, 31.9°C, 1.3°C RH = 58%, 98%, 6.65% ΔPMV = -0.67	80

5. This results in a final value of -0.60 for ΔPMV. The simulated PMV value (1.16) must be adjusted by this factor to take into account the results from the two field studies as shown in *Figure 5-4*. With the derivation of the weighted ΔPMV term, the field study based analysis and subsequent modification of PMV is complete.

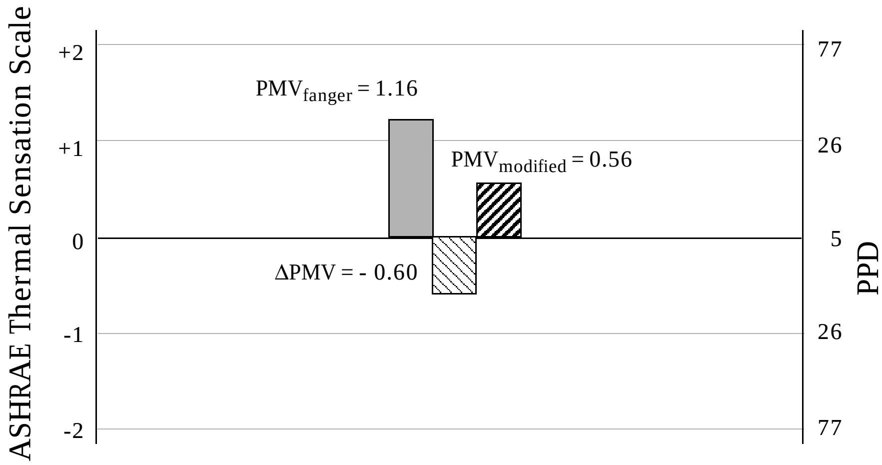


Figure 5-4: Modifying Fanger's PMV with field studies findings to maximize satisfaction

5.3 Bi-directional Functionality in TICO and SEMPER

5.3.1 Refining the Design Using Bi-directional Inference Mechanism in TICO

In case 1, a modification factor was applied to Fanger's PMV to account for deviation from the results in the matching case studies in the thermal comfort field studies database. The resulting value ($PMV_{modified} = 0.56$) is the target value for the implementation of the bi-directional functionality in the TICO module as developed in *section 4.3.2 on page 40*. The series of steps that are performed is outlined below:

1. The goal is to modify the design variables to satisfy $PMV_{modified} = 0.56$, the objective function in the current scenario. To bring about an adjustment of 0.46 in the current value of TICO's performance variable PMV (see *Figure 5-2*), the design variables defined in *Table 4.5 on page 43* along with their min, max and default values will be used. It is to be noted that this table lists these default values based on standards and heuristics but during the actual implementation, the designer has complete flexibility in defining any or all of these values to suit the context.

2. Once the performance variable has been identified and the objective function has been set, the next step involves deriving a preference index for each of the four design variables. This entails calculating the relative effectiveness and relative normalized distance attribute for the four design variables using the methodology developed in the previous section:

TABLE 5.6: Table showing the derivation of preference index for first iteration in case 2

Design Variable	Effectiveness [E]	Relative Effectiveness [E_{rel}]	Normalized Distance [D][a]	Relative Normalized Distance to Default [D_{rel}]	Preference Index [P]
Air Temperature	0.12	1	0.15	1	1
MRT	0.1	0.83	0.15	1	0.89
Relative Humidity	0.03	0.25	0.05	0.33	0.33

a. From *Figure 4-5 on page 44* and similar stepped function for air velocity and relative humidity

Both E_{rel} and D_{rel} range from a minimum value of 0 to a maximum value of 1. The preference index (after applying the respective weighting factors), therefore, can range from a minimum of 0 to a maximum of 1. The design variable having the highest preference index gets priority over other design variables. The steps involved in the derivation of the preference index is shown in *Figure 5-5*. The value of PMV changes from 0.1 to 0.22 after one iteration. The process is continued till the target value of PMV, in this case 0.56, is achieved.

3. In the current design situation where a HVAC system is responsible for maintaining indoor thermal conditions, TICO just requests the change in the design variable with the highest preference index and assuming that the HVAC system has been sized properly, the HVAC module fulfills the request. The process is repeated till the objective function is satisfied

   It is important to point out the difference in the bi-directional approach if the building under consideration has a passive system. In that case, TICO passes on to NODEM the preference index of four design variables. The design variable with the highest preference index, air temperature in this case, becomes the performance variable for NODEM, which may use its own set of rules to bring down the temperature by the requested amount. If NODEM can make this change and there are no objections from other SEMPER modules, the value is passed on to TICO. Else, NODEM repeats the step with the next variable on the list, in this case MRT. The entire sequence of events is described below:

   - TICO orders the design variables in decreasing order of priority from *Table 5.6*. Call it List A;

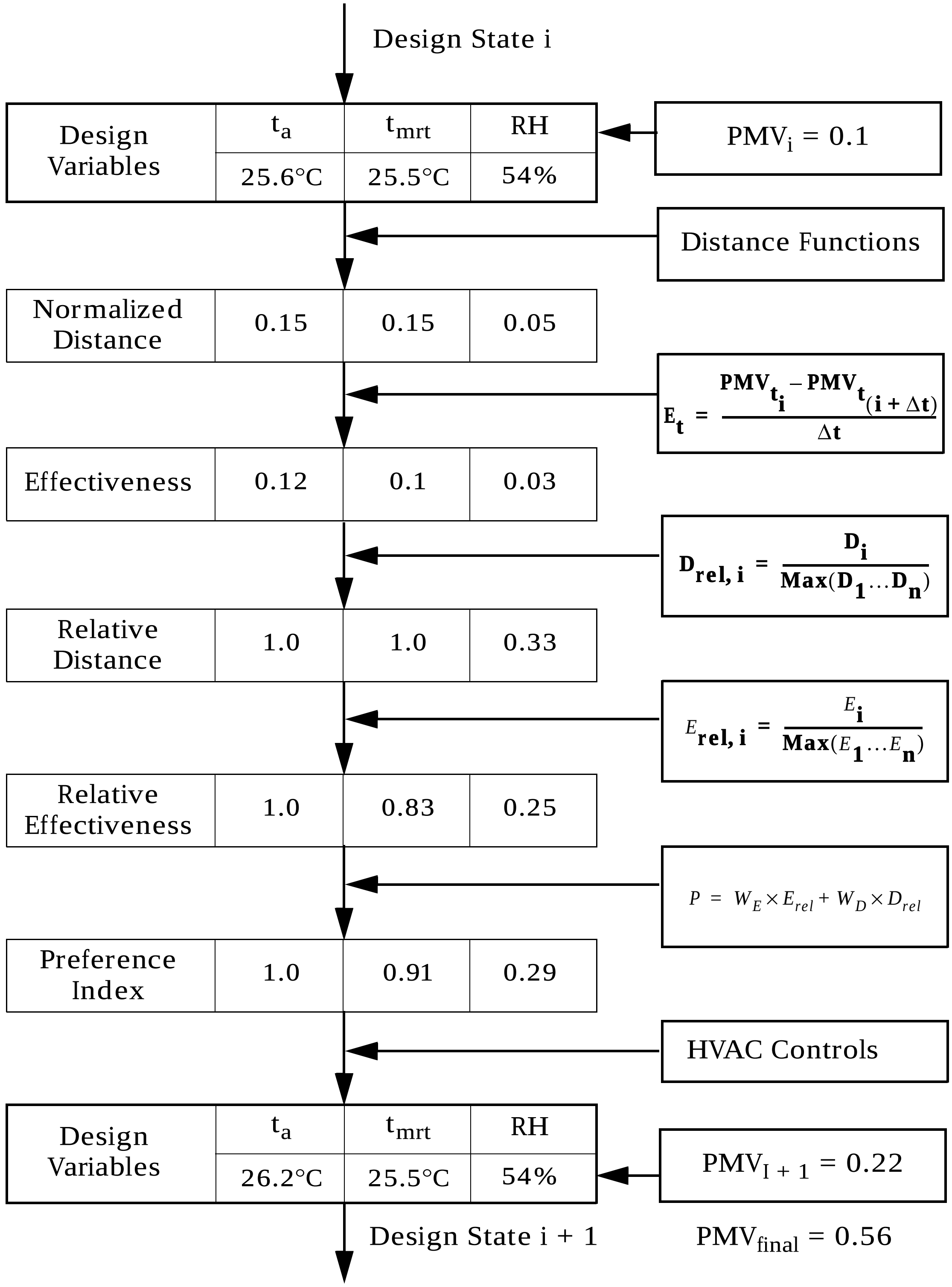


Figure 5-5: Step sequence in the bi-directional analysis

- TICO passes List A to NODEM and requests it to get the value of the performance variable close to the objective function;

- NODEM attempts to fulfil the request by trying the first variable in List A. If that does not work, it tries the next variable in List A and so on.

- If the request is fulfilled, TICO recalculates the value of $PMV_{modified}$. If the objective function is satisfied, it accepts the final set of environmental parameters and stops the execution. If the objective function is not satisfied, goes back to the first step;

- The iterations continue until either $PMV_{modified} = 0.56$ is fulfilled or NODEM cannot make any more requested changes in any of the design variables. In such a case, a sub-optimal solution is reached because of systemic or design limitations.

5.3.2 Prototypical Example of Bi-directional Functionality Using NODEM, TICO and BACH in SEMPER

The proof of concept for the integrated framework is demonstrated using a hypothetical scenario in which a designer explores certain design issues pertinent to the thermal performance of a single-story house (Mahdavi et al 1997). The design sketch is shown in *Figure 5-6*. The designer has modeled this house within SEMPER, as shown in *Figure 5-7*, which also shows the results of a passive thermal simulation carried out on the house. In addition to the temperature profiles window and the relative humidity profiles window, the PPD profiles window displays the PPD profiles in each space for a typical day of each simulated month. In this example, instead of changing the indoor environmental parameters — design variables for TICO, NODEM adjusts a different set of design variables that has a direct bearing on the prevailing thermal conditions in the house.

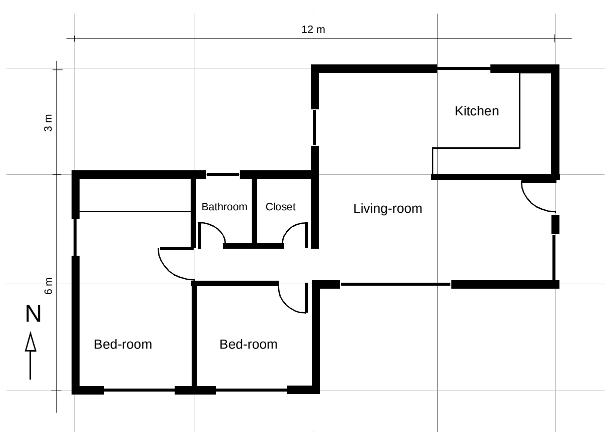


Figure 5-6: Schematic plan of the test case (a single-story house)

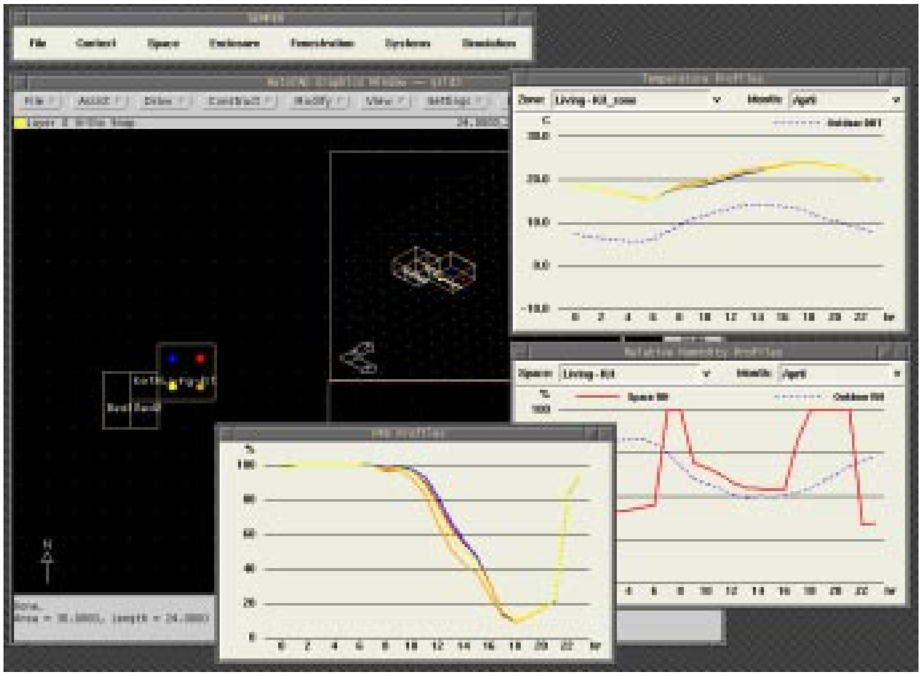


Figure 5-7: The SEMPER interface, showing the results of a passive simulation of the house

In this specific example, the designer is interested in exploring the trade-off between glazing area, glazing type, and floor mass on the mean PPD in the living area, under passive conditions. In order to perform the bi-directional analysis, the designer specifies the relevant design and performance variables. For this analysis, the designer will define the following design (DV) and performance variables (PV):

a) Percentage area of glass on the southern facade of the living area (DV);

b) Percentage area of glass on the southern facade of the bedrooms (DV);

c) Glazing type (DV);

d) Floor mass (DV);

e) Annual Mean PPD in the living area (PV).

In order to explore the interaction of these variables under different levels of natural ventilation, bi-directional analysis will be performed for different configurations of operable windows. Specifically, five different natural ventilation schemes were simulated in BACH, as indicated in *Table 5.7*.

Assuming the designer wants to decrease the mean PPD, she invokes the multiple design

TABLE 5.7: Different levels of natural ventilation explored in the bi-directional analysis

Ventilation Scheme	Percentage of window area left open		
	Winter	Swing	Summer
I	0%	0%	5%
II	0%	0%	10%
III	0%	0%	20%
IV	0%	5%	10%
V	0%	5%	20%

variable modification option. The bi-directional inference engine will continue performing iterations to reduce the mean PPD until the design and/or performance variable constraints make it infeasible to reduce it any further. *Figure 5-8* shows the design trajectory after 15 iterations, for ventilation scheme I. It may be observed in this case that the mean PPD has been reduced from about 60% to about 46%. This has been achieved by increasing the south glazing area in both the living and bedroom areas, increasing the floor mass, and changing the glass type. The average preference profile shows that these changes are desirable from a user-preference point of view.

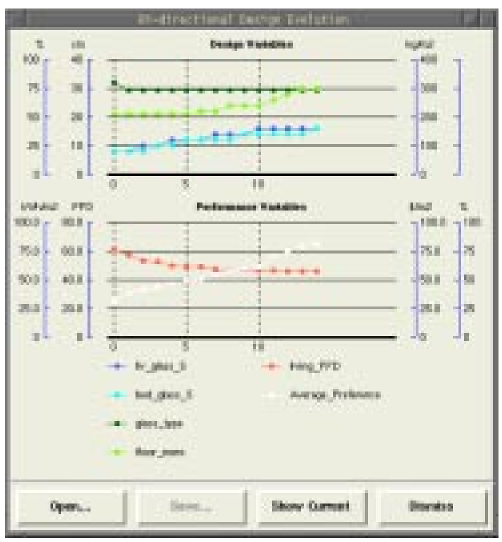


Figure 5-8: Design evolution trajectory after 15 iterations (ventilation scheme I)

The user then continues to perform the multiple iterations to reduce the PPD as far as the constraints will allow. The final design evolution trajectory is shown in *Figure 5-9*.

The trajectory reflects the trade-off between the design and performance variables at various design states for ventilation scheme I. In the final state, the mean PPD has

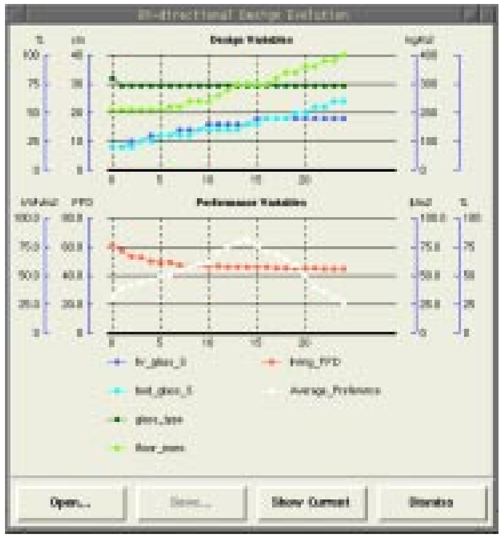


Figure 5-9: Final design evolution trajectory (ventilation scheme I)

reduced to a little under 45%. The floor mass has reached its maximum limit. Note that after iteration 15, the subsequent changes in design variables had a minimal impact on mean PPD, while significantly reducing average preference. Therefore, in this analysis, one might consider the design state at about the 15th iteration as *optimum* (*vis-á-vis* the *a priori* explicated preference functions). The designer could then run the bi-directional analysis on other ventilation schemes to observe the sensitivity of the variable trade-off analysis to different levels of natural ventilation. *Figure 5-10*, for instance, shows the design trajectory for ventilation scheme III. It may be observed that in this scheme, the trajectories of the design variables generally maintain the same trends as the previous ventilation scheme, although the mean PPD values are generally lower.

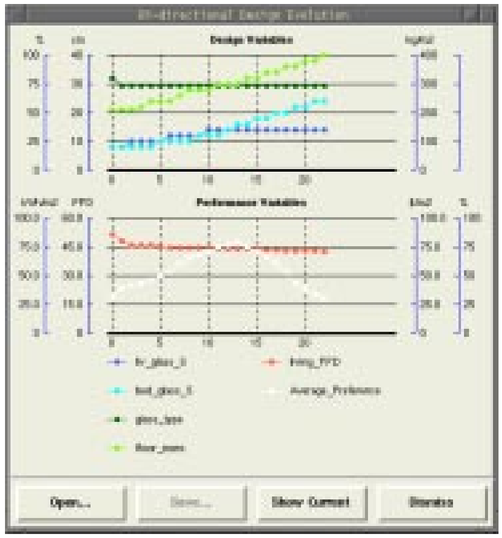


Figure 5-10: Final design evolution trajectory (ventilation scheme III)

6 Contributions and Future Research

6.1 CONTRIBUTIONS

The main contributions of this research effort are in line with the objectives set out in the first chapter:

1. *Implementation of industry-standard thermal comfort algorithms in an architectural design environment*

   It has been demonstrated that thermal comfort calculations can be integrated in a computer-aided architectural design environment just like any other performance simulation and can play a major role in optimizing energy use and enhancing thermal comfort in a building. This has been done by exploiting the inherent structural homologies between space-based design representation and thermal simulation tools. A prototype class hierarchy for thermal simulation related data was implemented within the framework of an object-oriented multi-performance simulation environment (SEMPER). TICO facilitates an interactive examination of a number of critical design parameters and their influence on the thermal environment. These may include:

   - Selection of enclosure components and their potential ramifications in terms of thermal comfort levels in the building in general and perimeter areas in particular;

   - Impact of natural ventilation on thermal comfort through a dynamic data transfer mechanism between NODEM, BACH and TICO.

   The technical contribution in terms of implementation of TICO are:

- Implementation of a steady-state (ISO 1994) and dynamic (ASHRAE 1992) model of the human body to evaluate thermal comfort in a flexible grid-based design environment;
- Using Predicted Mean Vote (PMV) to propose a richer set of environmental control strategies that go well beyond the conventional, mono-dimensional (thermostat based) control options currently available.

2. *Simultaneous evaluation of thermal and energy performance with thermal comfort*

   Unlike some other efforts in this field, prediction of thermal comfort is not an exercise in a vacuum. The SEMPER architecture allows a dynamic exchange of data among TICO, NODEM, BACH and HVAC modules facilitating simulations that very closely mirror reality. This framework creates a conduit for automatic input of parameters (from other modules of SEMPER) and output of thermal comfort indices and other information that can be used by the suite of thermal applications in SEMPER to improve the overall design of buildings.

3. *Field study based analytical support to fine tune thermal environment during early design stage*

   The knowledge based analytical capability of TICO was developed using the most comprehensive database of empirical experiments conducted to evaluate indoor thermal environments. The coupling of inferences from the field studies to comfort evaluation using classical thermal comfort algorithms helped formulate a flexible framework that can be used to perform a contextual thermal comfort analysis in a variety of settings.

4. *Enhanced preference-based performance-to-design mapping in the domain of thermal performance*

   A set of heuristics that looks at the complex relationship between environmental parameters and their influence on integrated thermal comfort index was used to refine the design. This was done by using the knowledge ingrained in TICO that helped it in predicting the changes in the environmental parameters to improve indoor thermal environment.

6.2 FUTURE RESEARCH QUESTIONS

As with any research effort, the scope of this dissertation was limited by time and constraints imposed by the requirements of the ongoing SEMPER effort. It is to be noted that SEMPER is still a prototype and there are clearly research areas where further work is required. Some of them are:

1. Using numerical algorithms for the calculation of shape factors so that mean radiant temperature calculation can be performed in non-orthogonal enclosures. The lighting module, LUMINA, which performs many calculations requiring the use of shape factors has already implemented a numerical algorithm and it is hoped that it can be adapted for mean radiant temperature calculations.

2. While suggesting a controls strategy, it would be useful if some of the adaptive thermal comfort algorithms (Auliciems 1981, de Dear and Schiller 1998, Humphreys 1976 and 1978, Nicol and Roaf 1996) can be integrated with the bi-directional inference mechanism of TICO.

3. The field study database that has been used in the analysis would contribute more toward the development of similar efforts in future, if it can provide some more information about the building itself in future. It is true that most of the missing information can be attributed to individual field studies but this database can be much more helpful if it had some of the data fields related to the following issues:

   - If the building has any history of occupants' complaints in the field of environmental conditioning;

   - If the building has ever experienced any case of building-related illnesses (BRI) or sick building syndrome (SBS). This may help in investigating the nature of relationship between thermal perception and serious indoor air quality problems;

   - The location of building especially if it is located in a heavily polluted area where outdoor air quality can be termed less than perfect;

   - The type of HVAC and air distribution system in the building. This may help researchers in understanding the systemic relationship between thermal comfort and HVAC systems.

4. Just like task lighting, task-based environmental control systems have the potential to achieve the twin objective of reducing both energy use and thermal dissatisfaction. However, more research and innovation is needed so that an effective communication channel can be set up between the controls hardware and software.

5. There are still some knowledge gaps in using a computational design architecture such as SEMPER to implement advanced control logic for building systems control and integration. In order for building controls to work smoothly, a very accurate prediction of prevailing conditions is required that entails smooth exchange of data between various sensors and different modules of SEMPER. Research efforts are already underway at the *Intelligent Workplace* to address some of these issues.

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A Glossary of Terms

To facilitate a better understanding, an explanation of the terms (along with their units) used in mathematical modeling of human body (both in Fanger's as well as Gagge's model) in *Chapter 2* follows:

M	Rate of metabolic heat production, $W \cdot m^{-2}$
W	Rate of mechanical work accomplished, $W \cdot m^{-2}$
E_{diff}	heat loss due to diffusion of water through skin, $W \cdot m^{-2}$
E_{rsw}	heat loss due to evaporation of sweat secreted due to thermoregulatory control mechanism, $W \cdot m^{-2}$
E_{res}	Rate of evaporative heat loss from respiration, $W \cdot m^{-2}$
C_{res}	Rate of convective heat loss from respiration, $W \cdot m^{-2}$
K	Rate of heat loss by conduction from skin to the outer surface of clothing, $W \cdot m^{-2}$
C	Rate of heat loss by convection from the outer surface of clothing to the ambient air, $W \cdot m^{-2}$
R	Rate of heat loss by radiation from the outer surface of clothing to the surrounding atmosphere, $W \cdot m^{-2}$
$C + R$	Sensible heat loss from skin, $W \cdot m^{-2}$
S_{cr}	Rate of heat storage in core compartment, $W \cdot m^{-2}$
S_{sk}	Rate of heat storage in skin compartment, $W \cdot m^{-2}$
$Q_{cr, sk}$	Rate of heat transport from core to skin (includes both conduction through body tissues and convection through blood flow), $W \cdot m^{-2}$
a	Fraction of body mass concentrated in skin compartment

$\dot{m}$ body mass, kg

$c_{p,b}$ Specific heat of body = 3.49 $kJ \cdot kg^{-1} \cdot K^{-1}$

q time, sec

R_{cl} Thermal resistance of clothing, $m^2 \cdot K \cdot W^{-1}$

h_c Convective heat transfer coefficient, $W \cdot m^{-2}$

h_r Linear radiative heat transfer coefficient, $W \cdot m^{-2}$

f_{cl} Clothing area factor, $A_{cl} \cdot A_D^{-1}$

p_a Water vapor pressure in ambient air, kPa

$p_{sk,s}$ Water vapor pressure at skin, normally assumed to be that of saturated water vapor at t_{sk}, kPa

$R_{e,cl}$ Evaporative heat transfer resistance of clothing layer (analogous to R_{cl}), $m^2 \cdot kPa \cdot W^{-1}$

h_e Evaporative heat transfer coefficient, $W \cdot m^{-2} \cdot kPa^{-1}$

w Skin wettedness, dimensionless

h_{fg} Heat of vaporization of water = 2430 $kJ \cdot kg^{-1}$ at 30 ^oC

$\dot{m}_{rsw}$ Rate at which regulatory sweat is generated, $kg \cdot s^{-1} \cdot m^{-2}$

$\dot{m}_{res}$ Pulmonary ventilation rate, $kg \cdot s^{-1}$

W_{ex} Humidity ratio of exhaled air, kg $H_2O \cdot$(kg dry air)$^{-1}$

t_{ex} Temperature of exhaled air, $^{\circ}C$

W_a Humidity ratio of inhaled (ambient) air, kg $H_2O \cdot$(kg dry air)$^{-1}$

$c_{p,a}$ Specific heat of air, $kJ \cdot (kg \cdot K)^{-1}$

PMV Predicted Mean Vote

I_{cl} Thermal Resistance of clothing, in $m^2 \cdot K \cdot W^{-1}$

t_a Air Temperature, in $^{\circ}C$

t_{mrt} Mean Radiant Temperature, in °C

v_{av} Relative Air Velocity, in $m \cdot sec^{-1}$

t_{cl} Surface Temperature of clothing, in °C

PPD Predicted Percentage of Dissatisfied

B Mean Radiant Temperature Analysis

B.1 GENERAL DISCUSSION

The enclosure surfaces which are found most often in a normal room are rectangular in shape (walls, ceilings, floors, windows, heating and cooling panels etc.) and this section concentrates on calculation of mean radiant temperature and radiation exchanges between a person and such practical surfaces.

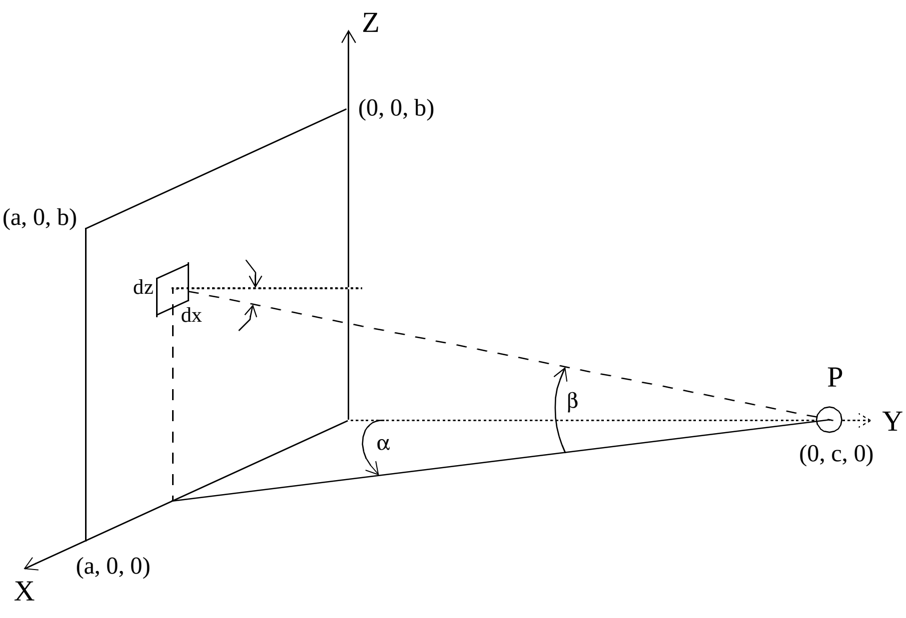

Figure B-1: Schematic representation for the evaluation of the angle factor between a person (at P on the Y-axis) and a rectangle ($a \times b$) in the X-Z plane.

Consider a person located in the orthogonal coordinate system (x, y, z) shown in Figure B-1:. The person faces the origin of the coordinate axis with his center at the coordinates (0, c, 0). The angle factor ($F_{P\text{-}A}$) between the person and the rectangle A ($a \times b$) is given by the following formulation. The actual steps involved in the derivation of *Equation B-1* can be found in books that have dealt radiation exchanges in greater detail (Fanger 1970).

$$F_{P-A} = \frac{1}{\pi} \int_{\frac{x}{y}=0}^{\frac{x}{y}=\frac{a}{c}} \int_{\frac{z}{y}=0}^{\frac{z}{y}=\frac{b}{c}} \frac{f_p}{\left[1 + \left(\frac{x}{y}\right)^2 + \left(\frac{xz}{y}\right)^2\right]^{3/2}} \, d\left(\frac{x}{y}\right) d\left(\frac{z}{y}\right) \quad \text{(B-1)}$$

The angle factor between a person and a vertical rectangle A located anywhere in the xz plane (see Figure B-2:) can be calculated using simple angle factor algebra:

$$F_{P-A} = F_{P-ABCD} - F_{P-BC} - F_{P-CD} + F_{P-C} \quad \text{(B-2)}$$

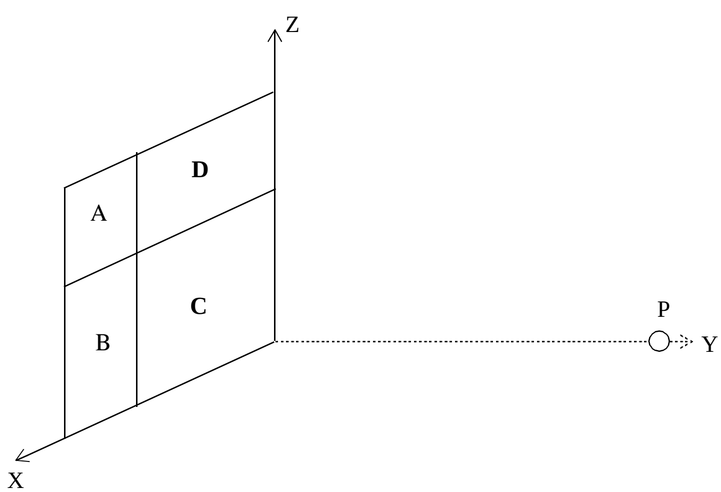

Figure B-2:Angle Factor Algebra

The mean radiant temperature now can be calculated from measured values of the temperature of the surrounding walls and surfaces and the relative position of the person with respect to these surfaces. As most building materials have a high emittance (ε), all the surfaces in the room can be assumed to be black, which enables us to use the following equation to calculate the mean radiant temperature with respect to a person placed in a room consisting of *n* isothermal surfaces (with temperatures t_1, t_2, ... t_n and angle factors between the person and the surfaces (F_{p-1}, F_{p-2}, ... F_{p-n}):

$$t_{mrt}^4 = t_1^4 \cdot F_{p-1} + t_2^4 \cdot F_{p-2} + \ldots + t_n^4 \cdot F_{p-n} \quad \text{(B-3)}$$

For small temperature differences between the surface of the enclosure, *Equation B-3* can be simplified to the following linear form that results in a slightly lower mean radiant temperature than *Equation B-3*. In most cases, however, the difference is small (for example, if half the surroundings ($F_{p\text{ - }N} = 0.5$) have a temperature 10 K higher than the other half, the difference between the two values would be ~ 0.2K).

$$t_{mrt} = t_1 \cdot F_{p-1} + t_2 \cdot F_{p-2} + \ldots + t_n \cdot F_{p-n} \tag{B-4}$$

Equation B-4 can be further simplified if the complex geometry of a person is reduced to a point. In this case t_{mrt} can be computed using the following formulation:

$$t_{mrt} = \frac{t_1 \cdot \Omega_1 + t_2 \cdot \Omega_2 + \ldots + t_n \cdot \Omega_n}{\Omega_1 + \Omega_2 + \ldots + \Omega_n} \tag{B-5}$$

In the above equation, $\Omega_1, \Omega_2, \ldots \Omega_n$ are the solid angles (in steridians) subtended from the reference point to the isothermal surfaces of the room. For the simple case of a rectangular surface and a point perpendicular to one of the corners of this rectangle (see Figure B-1:) the solid angle is given by:

$$\Omega_p = \operatorname{asin}\left[\frac{\frac{x}{y}}{\sqrt{1 + \left(\frac{x}{y}\right)^2}} \cdot \frac{\frac{z}{y}}{\sqrt{1 + \left(\frac{z}{y}\right)^2}}\right] \tag{B-6}$$

This helps in calculating the mean radiant temperature if the surface temperature and the geometrical attributes of indoor spaces enclosed by those surfaces are known.

C Implications of Indoor Climate Control for Comfort, Energy, and Environment

C.1 Introduction

In the last few decades the notion of environmental control (particularly the thermal environment) has emerged as a mega-industry. This as such remarkable development appears to be (at least implicitly) based on two basic assumptions:

- Total indoor environmental control is possible and effective regardless of the outdoor climatic conditions.
- Maintaining a predefined set of environmental conditions assures the comfort and satisfaction of inhabitants.

These assumptions must be critically reviewed, if one hopes to gain an understanding of the *status quo* and an idea of possible future developments in the area of environmental control. Toward this end, Human Ecology can provide not only a suitable epistemological framework, but also original insights as to the desirable directions in future research.

C.2 Control and Entropy

Human beings have always actively shaped their habitats, or as Banham maintains, deployed technical resources and social organizations, "in order to control the immediate environment: to produce dryness in rainstorms, heat in winter, chill in summer, to enjoy acoustic and visual privacy …" [1, pp. 18]. One may refer to this act of shaping (or gestalting), if prepared consciously and in an organized manner, as environmental design. Utilizing the conceptual framework of Human Ecology [2, 3], one could derive a provisional cybernetic view of this design activity:

> As a process, designing involves the development of a set of related (coherent) formal (spatial) configurations, and organizational (functional) layouts, as well as the concrete (physical) realization thereof, with the (*a priori* expressed and/or *a posteriori* deducible) "intention" of favorably influencing the relationship between the ecological potency of human beings and the ecological valency of their surrounding outside world, while responding to requirements implied by both "real" (first) and "symbol" (second) functions [4, pp. 531].

Ecological potency denotes here the totality of the characteristics of human beings in their distinctions realized at the respective point in time and considered in their significance as related to the encounter with their surroundings. Ecological valency denotes the totality of the characteristics of the surrounding outside world in their distinctions realized at the respective point in time and considered in their significance to the relevant human beings. It is important to understand that the above definition is not the continuation of the behavioristic error on a higher strategic level. It is not implied that a perceived imbalance in the (ideally homeostatic) relation between ecological valency and ecological potency triggers design activity, quasi in the way behaviorists thought stimuli trigger responses.

Based on the historical evidence of evolving human habitation patterns, one could probably imply a trend away from (human) "self-adaptation" toward adaptation of the surrounding context. In this context, the evolution of the building activity appears as a set of variations on a theme dedicated to the nature of the interrelations between the ecological potency of human beings and the ecological valency of their outside surrounding world:

> "First, there is man's habit of changing his environment rather than changing himself. Faced with a changing variable (e.g., temperature) within itself which it should control, the organism may make changes either within itself or in the external environment … In evolutionary history, the great majority of steps have been of an intermediate kind in which the organisms achieved change of environment by change of locale … "[5, pp 445].

In fact, one could interpret the periodic migration of nomads (biannual change of location in pursuit of a better climatic "match") as motivated by the differential between ecological potency and ecological valency. In this context, nomads' active change of location can be seen in contrast to the creation of permanent built structures that provide artificial conditions more responsive to attributes of the ecological potency. Starting from this point, the evolutionary development of the building activity appears to be that of successive increase in the "environmental" adaptive efficiency (i.e. increased potential for creating and maintaining artificial and adaptable surroundings).

Certain products of the so-called "traditional architecture" demonstrate intermediate cases where buildings allow for the reduction of human exertion and provide a more adaptable valency context [6]. A good example of this adaptive strategy is the traditional "2-zone" house on the north coast of Oman that integrates a winter residence and a summer residence (thus involving a mild form of biannual migration). The characteristic differences of the constructions of these two units (e.g. the lightweight construction and the air-permeability of the summer residence and the rather massive and well-insulating construction of the winter residence) allow for maintaining more or less acceptable potency/valency-relations for various prevailing local climatic conditions.

Given the limited availability of energy resources prior to the industrial revolution, judicious (environmentally responsive) design of building structures practically remained the only way to alleviate the impact of the climatic extremes on human habitation. Numerous examples of contextually adopted vernacular architecture in various climatic regions are known and well-documented [6, 7, 8, 9].

As from late nineteenth century, the efforts toward augmented control over "environment" have been increasingly directed toward the use of more or less energy-intensive building service technologies. Fanger’s reflections on the definition of thermal comfort fit in this context:

> "Creating thermal comfort for man is a primary purpose of the heating and air conditioning industry, and this has had a radical influence on the construction of buildings … and thus on the whole building industry. Viewed in a wider perspective, it can perhaps even be maintained that man's dependence on thermal surroundings is the main reason for building houses at all, at least in the form in which we know them today" [10, pp. 14].

This "industry-based" approach to creating thermal comfort can be seen as the continuation of the efforts toward the reduction (or even elimination) of "man’s dependence on thermal surroundings" while further reducing the need for human exertion. This implies in human ecological terms, that desirable valency attributes are intended to be achieved not by "passive" methods (nomad’s long-distance migration, or "mini-migrations" within 2-zone traditional houses, or static structural features of the built habitat), but by controlling the thermal comfort parameter in spaces through "power-operated" mechanical means.

Celebrating the achievements of "power-operated solutions" (air conditioning units), Banham wrote:

> "... it is now possible to live in almost any type or form of house one likes to name in any region of the world that takes the fancy. Given this convenient climatic package one may live under low ceilings in the humid tropics, behind thin walls in the arctic and under uninsulated roofs in the desert. All precepts for climatic compensation through structure and form are rendered obsolete …" [1, pp. 187].

The intentional *leitmotiv* (purposive consciousness in Bateson terms) of the recent trends toward the so-called "intelligent" buildings appears to be the provision of even more control while further reducing the need for exertion. A typical example of this view is expressed in the following newspaper excerpt addressing "intelligent" features of an office building erected by a Japanese construction company that intends to offer the very latest in workplace comfort:

> "Employees will each carry an identification card that holds personal data on his or her favorite room temperature and level of brightness. These cards will transmit the data on an electric wave to sensors installed in the walls. The sensors will then detect who is nearby at one given time, and automatically set the appropriate level of lighting, heat or air conditioning" [11].

Based on the prior discussion, one may now confidently conclude that, firstly, there has been a significant increase in human control over her "immediate" surrounding, and, secondly, the degree of this controllability has increased sharply due to (relatively) recent availability of power-operated mechanical means for environmental control. The question is, however, if one can justifiably conclude that total indoor environmental control is *possible* and *effective* regardless of the climatic context?

As shown earlier, there appears to be no doubt in Banham's mind that mechanical systems provide for comprehensive and total control:

> " … we now dispose of sufficient technology to make any old standard, norm or type habitable anywhere in the world. The glass skyscraper can be made habitable in the tropics, the ranch-style split level can be made habitable anywhere in the US" [1, pp. 288].

Nowhere in "Architecture of the Well-tempered Environment" does Banham question if these systems *de facto* deliver what they have promised or are expected to deliver. Faced with this question and having the advantage of historical hindsight, we may actually speak of a "control myth".

In the best of all worlds, a competently designed, installed, operated, and maintained mechanical system could theoretically provide a high level of indoor environmental control, given a static building use scenario. Alas, there is abundant empirical evidence that many mechanical building service systems (particularly the HVAC installations), due to a wide range of circumstances (extremely inappropriate "structural" solutions, bottom-line oriented poorly designed service systems, incompetent execution, poor maintenance and operation, post-installation changes in building use and occupancy, lack of systems integration, etc.), do not provide the expected and required range of environmental conditions [12, 13, 14]. Cases of poor performance due to misplaced and/ or defective thermostats, deficient zoning and control options, inflexible load capacities and distribution patterns, mislocated air-intake and exhaust openings, short-circuiting supply and return air paths, etc. can be listed *ad nauseam*. Recent literature is filled with damaging accounts of air quality problems (e.g. stale air, high levels of pollutants' concentration), hygienic deficiencies (e.g. mold growth), discomfort complaints, and the range of the problems associated with the "sick buildings syndrome" (SBS) [15, 16].

As to the question of "effectiveness", Banham's position is even more disturbing. The few references to the implications of the widespread use of mechanical means for thermal conditioning of the indoor environment are limited to first-cost economical matters. There is repeated reference to "abundant timber" and "abundant fuel" in North America and an uncritical internalization of "cheap-fuel economy" as the all decisive design context. Architects are primarily criticized not because they failed to offer energy-conscious (e.g. passive) alternatives to the emerging energy-intensive air conditioning technology, but mainly on their failure to rapidly and "neatly" integrate them in their designs:

> "Although many architect-designed buildings are now beginning to make their peace with seemingly inevitable eruption of room-conditioners on their facades, few have set out to exploit the neat visual detailing of their intake grilles, nor the convenience for interchangeability of their easy installation and removal" [1, pp. 192].

Banham goes so far as to declare Philip Johnson's extremely problematic all-glass design for his own house as a "unique example of environmental management" downplaying the designs' "serious shortcomings in its environmental performance". The same trivializing attitude can be found in his comments on the "tyranny of the ancestral and restrictive vernacular" and the "attractiveness of the sealed and necessarily mechanized envelope of glass slab office towers":

> "The present generation of experts on tropical architecture … seem to regard the glass skyscrapers that have appeared in developing countries as mere status symbols … They

> may well be succeeded by a generation of experts on architecture in the temperate zones who wish that our Western civilization had been capable of making as bold a break with its ancestral vernaculars as the Africans have been" [1, pp. 288].

We have extensively quoted these sadly outdated passages, as they appear to be, surprisingly, still representative of the mind-set and actual decision making patterns of most building clients, designers, and engineers. Still in 1995, a publication can appear that *de facto* summarizes the millennia tradition of refined passive building methods of indigenous cultures with this unbelievable statement by Nagengast:

> "Once upon a time, our ancient ancestors were superstitious concerning the forces of nature. Their indoor environment was determined to a large extent upon the conditions outside. As knowledge began to replace superstition, our ancestors fashioned the first crude indoor environmental control" [17].

North America is, despite the energy crisis of the seventies (of which Banham could not know, while Nagengast should have certainly remembered) and despite the ecological movement, still a "cheap fuel economy". And fully air conditioned energy-hungry "glass skyscrapers" still appear (in fact with increasing frequency) in developing countries.

Be that as it may, an enormous price has been and is being paid for the "power-operated" approach to increased environmental control, namely an explosive growth in the exploitation of the planet's finite energy resources (particularly nonrenewable fossil fuels):

> "The United States has already misallocated something like two hundred million tons of cooling capacity and 200 peak gigawatts of power supply to run it, at a total marginal cost approaching $1 trillion, through failure to optimize the buildings' capacity that was installed in" [18].

Moreover, this excessive energy consumption is accompanied by an accelerated environmental degradation. Commenting on the devastating effects of the North-Americans' "conspicuous consumption" and their daily energy "potlatch" (so that the "Thunderbird may keep things rolling along"), Prins maintains:

> "The rest of the world has to pay a pretty heavy price on their behalf, perhaps least contentiously in foregone future options on wasting assets being consumed now (e.g., four million barrels of oil per day to feed the Thunderbird, as against one million for Africa, Asia and Latin America combined) … More and more it appears that the price is most meaningfully displayed as the proportionate American contribution to general pollution, of which perhaps the single best index is of the emission of 'greenhouse gases' which contribute to global warming … Expressed as tons of carbon per person per year released into the atmosphere, the USA today leads the world at over 3.75 tons … If we care to continue this global experiment at this rate, we shall soon enough find out the

> answer. Unfortunately, by that moment it will be, by definition, too late to do anything about it" [19].

In cybernetic terms, the industrial approach has been able to decrease selectively the negative entropy in the subsystem human habitat (e.g. through maintaining large indoor-outdoor temperature gradients even under extreme climatic conditions and inside poorly designed building structures). However, this has been achieved by an accelerated entropy increase in the encompassing system that includes human habitats, namely the planet earth.

There is ample evidence implying that the pace and magnitude of man's impact has most probably surpassed the maximum adaptation rate of the ecosystems. And the vast energy requirements of a largely power-operated built environment are not an insignificant component of a general approach to "civilization" that is responsible for such circumstances as the rapid depletion of planet's limited fossil fuels, high levels of tropospheric ozone, the damage to the stratospheric ozone layer, the continuous increase in carbon dioxide concentration (contributing to the green house effect and the global warming risk), rapid global deforestation, large-scale pollution of air, water, and soil, extinction of whole animal and plant populations, etc. Bateson appears to have referred to all this, when he wrote:

> " … the power ratio between purposive consciousness and the environment has changed rapidly in the last one hundred years, and the rate of change in this ratio is certainly rapidly increasing with technological advances. Conscious man, as a changer of his environment, is now fully able to wreck himself and the environment - with the very best of conscious intentions" [5, pp 445-446].

C.3 IS "COMFORT" PREDICTABLE?

It should be clear at this point that the power-operated energy-intensive approach to (thermal) environmental control has, on many occasions, failed to provide the targeted conditions. Furthermore, the state of art in design and operation of most mechanical air conditioning systems must be regarded as ineffective in any evaluation framework that goes beyond measures that are indifferent ecologically and short-term (first cost-based) economically. Let us assume now, for argument's sake, that there are building service systems and technologies that in fact maintain *exactly* and *effectively* a predefined set of environmental conditions throughout the *entire* interior spaces of buildings. We still have to deal with the question if there is, in fact, a "predefined set of environmental conditions" that, if offered, would assure the comfort and satisfaction of the inhabitants.

In order to answer this question, one would have to address the historical development of thermal comfort indices. A brief review of this background reveals two basic trends:

- The "scientific" approach to thermal comfort research has aimed at identification of measurable environmental indicators with the hope of correlating those with people's perception and evaluation of thermal conditions (thermal sensation vote);
- Historically, a trend may be postulated toward identification of an increasing number of comfort-relevant environmental (and occupancy) indices and an increasing level of refinement and detail in their description.

Looking back to late nineteenth century, the room air temperature appears to have been the primary candidate for the description of thermal requirements, although, initially, without systematic studies on its actual relevance for human evaluation purposes. Baldwin simply stated that it is "usual" to maintain a temperature of 70°F within a room [20, pp. 34]. The same unreflective attitude regarding the preferable temperature range is also present in Corbusier's perplexing "eternal" attachment to a 18°C air temperature:

> "Every nation builds houses for its own climate. At this time of international interpenetration of scientific techniques, I propose: one single building for all nations and climates … The buildings of Russia, Paris, Suez or Buenos Aires, the streamer crossing the Equator, will be hermetically closed. In winter warmed, in summer cooled, which means that pure controlled air at 18°C circulates within for ever" [21, pp. 64ff].

A major systematic effort toward multi-criteria comfort description frameworks started in early 1920’s at the research facility in Pittsburgh. Experiments involving human subjects were conducted in a controlled context, and the so-called *Effective Temperature* was derived, which combined the effects of air temperature and relative humidity into one index. *Effective Temperature* is defined as an arbitrary index which combines into a single number the effect of dry-bulb temperature, humidity and air motion on the sensation of warmth or cold felt by the human body. The numerical value is that of the temperature of still saturated air which would induce an identical sensation [22].

The post world war II economic recovery and the rapid growth of the HVAC industry in the late 60’s and early 70’s led to a flurry of activities in the field of thermal comfort research. Significant contributions were made, among others, by Fanger and Gagge toward development of comfort indices that would reflect the combined effects of various environmental variables. Their comfort indices are structured in such a way that a given value of the index corresponds to a particular thermal state of the body. However, they differ in the way they define this state. Nonetheless, both Gagge’s *Standard Effective*

Temperature (SET) and Fanger's *Predicted Mean Vote* (PMV) aim at integrating all the relevant environmental and personal variables toward predicting the occupant's thermal comfort conditions.

Fanger introduced the so-called PMV, which was based on a steady-state model of human body (in a state of thermal equilibrium with negligible heat storage). The earlier comfort indices were generally the result of statistical analysis of a limited set of experimental data. Each index therefore strictly applied to the range of physical conditions that was covered during a specific set of experiments. Fanger tackled the problem of producing a comprehensive comfort index by starting from the premise that it is possible to define the comfort levels in physical terms that are pertinent to body's thermal regime. In this perspective, the state of long-term thermal balance is the necessary condition for thermal comfort, i.e. the rate of body's heat loss to the environment must be equal to the rate of heat production in the body. Fanger used classical heat transfer theory and empirical studies to derive the general comfort equation which captured four environmental variables (air temperature, mean radiant temperature, air velocity and relative humidity) and two personal variables (activity level and clothing). The representation of all the six variables and their relationship to the thermal sensations in the comfort equation was a very significant step as it provided for a way to evaluate any thermally controlled environment. McIntyre very succinctly notes this contribution:

> "Fanger's recognition that the comfortable levels of skin temperature and sweat rate were affected by activity level allowed the construction of the very successful general comfort equation, which can be applied over a range of conditions" [23, pp. 177]

The satisfaction of the general thermal comfort equation is a necessary condition for maintaining thermal comfort. The comfort equation as such does not specify people's level of discomfort where this condition is not met. Fanger therefore, derived a relationship between people's thermal sensation, as expressed on ASHRAE's 7-point scale, and the thermal variables occurring in his comfort equation. The assumption was that "the thermal sensation at a given activity level is a function of the thermal load of the body, which is defined as the difference between the internal heat production and heat loss to the actual environment for a person hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level" [10, pp. 111]. Toward this end, PMV is thus defined as the mean response of a large group of people according to the ASHRAE thermal sensation scale. The complex expression to calculate PMV is actually a curve-fit which was constrained to pass through the point for sedentary activity. This partly explains the good agreement between the values predicted by Fanger's comfort equation and the experimental studies that were conducted later using sedentary subjects. From PMV, one can further derive the Predicted Percentage of Dissatisfied (PPD) using a diagram [10] or an expression [24] which predicts the percentage of dissatisfied people for the environment under consideration.

Gagge defined a new effective temperature called *Standard Effective Temperature* using a two-node (core and body) model of human body [25]. This concept assumes a dynamic exchange of energy between the two compartments through direct contact and thermoregulatory controlled peripheral blood flow which is dependent on ambient conditions [26]. SET involves both mean skin temperature and skin wettedness to define the thermal state of a person. It is reasonable to say that thermal sensation based on SET depends on skin wettedness in hot environment and skin temperature in cold environment.

The evaluation of SET for a given set of conditions requires a two-node dynamic mathematical model of thermoregulation. Instead of assuming a steady state condition, Gagge assumed that a transient energy balance exists between the two nodes [25] and that the rate (time dependent dynamic nature) of heat storage equals the net rate of heat gain minus the heat loss. The rate of change in internal energy can be written separately for each compartment in terms of thermal capacity and time rate of temperature change in each compartment [26]. SET is calculated as the temperature of an isothermal environment (where air temperature is equal to mean radiant temperature, relative humidity is 50% and air is still) in which a person with a standard clothing insulation would have the same heat loss at the same mean skin temperature and the same skin wettedness as she has in the actual environment and with the actual clothing insulation under consideration. Although SET is probably the most general thermal comfort indices, it was particularly designed for dealing with the effects of high humidities and temperature.

Our schematic review of the evolution of thermal comfort research demonstrates a process of continuous refinement of increasingly comprehensive predictive models based on classical heat transfer, body's physiological processes, and statistical analysis of human perception. In particular, Fanger's PMV and Gagge's SET form the basis of such internationally reputed standards as ISO 7730 [24] and ASHRAE Standard 55-92 [27].

The important question that now arises is the applicability of these models and their derivative standards in real world situations. Certain basic problems in model validations are due to the empirical nature of most of the required input parameters. Many empirical constants must be derived experimentally and, despite years of research, there are still problems in accurately predicting their values. One example is the convection coefficient which can be calculated in multiple ways [23, 26]. Other examples are skin temperature and skin wettedness, two variables which form the basis of SET. These have been assumed to be uniform over the whole body which may not be the case in actual situation.

However, an even more important problem may be related to the requirements of "controlled" parametric studies. Much as the researchers would have liked to base their findings on "real-world" situations, these requirements have often led them to perform their experiments solely in climate chambers where the factors influencing thermal comfort can be selectively measured and closely monitored. This controlled research design which may have permitted the relative importance and interactions of several independent variables to be disentangled involves, unfortunately, the risk of reducing complex comfort evaluation process to rather simplistic stimulus-response patterns [28]. Environmental psychologists and experts in human ecology have long contended that the result of laboratory studies should be applied with care, as they often involve crude oversimplifications of the interactions between people and their surroundings [3, 29, 30].

In this context, it may be helpful to mention the results of certain field studies that have been conducted to answer specific questions regarding the applicability of "universal" comfort prediction models. As already discussed, Fanger's largest contribution was the introduction of a comfort model with "generic" character which was sorely missing in earlier field studies. A number of recently conducted field studies [30, 32, 33] involved the comparison of the results obtained from field data with predicted values using comfort models (in situ measurement of the environmental and behavioral variables known from climate chamber experiments to influence thermal comfort).

The results of these experiments have not always supported those of climate chamber method. Thus, the thermal comfort researchers have been confronted with the problem of accounting for this discrepancy in a consistent and scientific way so that either changes can be incorporated in the standards or some alternative approach can be found toward enhancement of the thermal conditions for occupants in real world situations.

Numerous potentially contributing factors have been suggested to explain the above mentioned discrepancies between comfort model predictions and the results of field studies. These include:

- difficulties in accurate estimation of certain empirical constants and coefficients that are utilized in the underlying mathematical algorithms of comfort prediction models;
- difficulties in precisely determining occupancy factors (such as activity levels, clothing insulation, furniture effects) in real world settings;
- field complexity of certain environmental factors (asymmetric radiant fields, complex air movement patterns and related occurrences of draft and turbulency, significant vertical temperature gradients, etc.);
- interference effects of certain personal factors that comfort models may have ignored unjustifiably (differences in age, gender, ethnic and cultural background, etc.);
- dynamism and variance of both environmental conditions (*ecological valency* in human ecological terms) and occupants' status, activities and behavior in the field (*ecological potency* in human ecological terms); and
- possible synergistic interactions between thermal conditions and other relevant surrounding factors (visual parameter, acoustic conditions, etc.) in view of the overall (informatory) environmental evaluation.

One might argue that, principally, all of these issues may be interpreted as "noise" phenomena in the inherently statistical relationship that comfort models imply between environmental (and occupancy) factors on one side and the thermal sensation vote on the other side. In fact, the statistically relevant relationship between the Fangerian terms PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) implies that even given "optimal" thermal conditions (PMV = 0), PPD would be non-zero. This may have been part of the reason, why certain comfort standards [27] assume that thermal comfort requirements for an indoor space are fulfilled if no more than 20% of the occupants are dissatisfied with thermal conditions in the environment.

However, there are serious problems with this attitude. As mentioned earlier, field studies indicate that actual dissatisfaction rates may be significantly higher than those foreseen in the standards and expected based on comfort model predictions. Considering the evidence collected in the field and given the fundamental complexity, variance, and dynamism of the relationship between people’s ecological potency and the ecological valency of their surroundings, it is safe to postulate a certain "systemic" limit in predictability of thermal comfort and thus in provision of maximum thermal satisfaction in *uniformly* conditioned indoor environments. Furthermore, even if it would be possible to confidently predict that a certain percentage (say 80%) of the inhabitants will be thermally comfortable given a set of predefined thermal conditions, we would still have to seriously question the admissibility of the simple exclusion of a large number of people as thermal "outcasts".

C.4 IN SEARCH OF NEW PARADIGMS

Looking back to our initial questions, we have come now to some sobering conclusions. All is not well with the design and operation of mechanized indoor environment control systems which, in some instances, even fail to provide their - rather narrowly defined - target environmental conditions. Furthermore, there is most probably a "system-immanent" limit in the percentage of people who would be thermally comfortable in a *centrally* and *uniformly* conditioned space no matter how carefully the thermal parameters are selected and maintained.

These views are shared by an increasing number of researchers, engineers, and designers in search of or in the process of experimenting with new approaches and alternative ways in dealing with the problem of defining and providing adequate thermal conditions in the built environment. In this context, we will focus on two recent groups of ideas/efforts that we label - somewhat arbitrarily - "exoteric" and "esoteric".

The "exoteric" approaches do not question as such the notion of thermal comfort and even the possibility of measuring it through thermal sensation votes utilizing well-known "psycho-physical" scales. They also appear to accept the "classical" terminology of thermal comfort research concerning the matrix of those environmental variables and occupancy factors that are believed to be relevant to people’s perception and evaluation of the thermal conditions. What these approaches question is the appropriateness of *uniform* environmental conditioning in all but single-occupancy spaces. In fact, one abandons altogether the notion of minimizing the number of dissatisfied in uniformly conditioned spaces and allows instead for a flexible multi-zone context that can be differentially and dynamically controlled by individual occupants. This involves, from the human ecological point of view, "intelligent" building hardware, energy systems, and control technologies to provide high levels of personal control and thus a potentially wider range of possibilities to maintain adequate relationships between inhabitants' ecological potency and their surroundings' ecological valency.

In the domain of office design, implementation efforts have been focussed on occupant-controlled desktop task conditioning systems. These systems have been variously referred to as "task conditioning", "localized thermal distribution", and "personal air-conditioning" in technical literature. As in the case of task lighting, the controls for these systems rest partly or entirely with the occupants. Typically, the occupant is given the possibility to manipulate a number of environmental variables (particularly air temperature, volume and velocity) in the near vicinity to satisfy her personal thermal comfort requirements [34]. One such system provides direct access to supply air (speed, direction and temperature of air can be controlled). An infrared sensor continuously monitors occupancy for automatic on/off control if the user is absent for 10 minutes. An optional under desk radiant heat panel is capable of providing localized heating [35]. By giving freedom to occupants to adopt their immediate surroundings, one hopes to specifically counteract problems arising out of inter-individual differences. At the same time, this process of partly transferring the controls to occupants may, psychologically, elevate the level of satisfaction with the thermal conditions while relaxing the requirements concerning the "comfort variables" of the ambient environment.

As compared to large uniform conditioning systems, user-based environmental control systems undoubtedly represent a major step forward. There are, however, still some points of concern, that future research must address: *a)* User-based systems treat the environmental factors in a rather "sterile" (almost reductionist) manner. For example, "air flow" is typically maintained through highly directional micro-terminals reminiscent of overhead air nozzles in airplane cabins; *b)* Furthermore, this "reductionist" mode of dealing with environmental factors are realized in hermetically sealed buildings with no or little "immediate" environmental contact with the outside world; *c)* The functionality of user-based systems is technically achieved by adopting a thermally asymmetrical conditioning mode (air movement and radiation is directed on some parts of body and not on others) and more research is required to fully understand the overall long term implications of this approach [34]; *d)* A task-based local concentration of environmental services may further intensify the confinement of workers already limited in their spatial movement due to small workplaces configurations such as office cubicles.

At the heart of many of these concerns is probably a sense that even user-based systems (at least in their current technical realizations) do not sufficiently address the potential implications of differential stimuli (e.g. certain fluctuations of environmental patterns), environmental contact, and informational factors (semantic attributions, social and cultural expectations, etc.) for the inhabitants' overall sense of well-being.

In order to deal with these questions at some reasonable level of resolution, we now turn our attention to certain "esoteric" views and approaches that share a common feature: They all, to various extents, challenge, question, or transcend all or certain aspects of the premises behind the classical thermal comfort models and the associated technological approaches toward environmental control.

C.4.1 ENERGY AND INFORMATION

Human ecology postulates the relevance and importance of both *matter-energetic* and *informatory* aspects of human-environment-interactions for the perception and evaluation processes [2, 36, 3]. This is even recognized - at least theoretically - by ASHRAE's own definition of thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" [27]. According to human ecological terminology, a *material-energetic aspect* as well as an *informatory aspect* can be assigned to every entity, state, process. The material-energetic aspect refers to the assumption that there is nothing called "existing" unless some amount of matter and/or energy is involved. The informatory aspect refers to the assumption that matter/energy has a certain distribution in space and time which can be understood as a structure. An information content can be correlated to this structure. In praxis, the matter-energy aspect is considered more commonly, perhaps because it can be quantified more conveniently. However, these two aspects are complementary and inherent to any environmental relationship.

Classical thermal comfort research has treated people as a rather passive "element" of the thermal exposure conditions. However, due to their internal information processing processes as well as their "effectors", human beings can potentially affect external entities which in turn affect their internal "model environment" [2, 36]. The (explicit or *de facto*) reduction of these systematic relations to mechanistic "stimuli-response" chains may result in significant conceptual and strategic shortcomings in environmental design activities:

- The complex pattern of surrounding factors may be taken into consideration only to the extent of its description in terms of easily measurable (energetic) variables (such as air and mean radiant temperature, relative humidity, etc.);
- The informatory aspects of environmental relationships, especially with regard to the so-called "Uexküll-transformation" may be ignored or insufficiently considered;
- The inhabitants may be viewed in dissociation with their experience and background, status, and goals and treated merely as "generators" of statistically relevant data;
- The dynamic interactions between two autonomous activity centers ("inhabitants" and "surroundings") may be conceptually ignored and practically hindered.

Similar concerns have been voiced (albeit probably with a lesser degree of theoretical rigor) by many other researchers while commenting on the possible explanations for the aforementioned discrepancies between the result of field studies and comfort model predictions. They argue that the perception of the thermal comfort may be affected by personal and contextual factors not imagined and thus not considered by the experimenters. In particular, they maintain that the perception process is not solely governed by the so-called environmental "stimuli" and the primary physiological "responses". Rather, it must be studied in the broader context of cognition, memory, expectation, and intentional behavior [37, 38].

C.4.2 CHALLENGING THE UNIVERSALITY ASSUMPTION

In the first half of this century, there was a general understanding that comfort-zone requirements should be different for summer and winter. Several studies in USA and in England reaffirmed these differences [39, 40]. However, in 1960's, there were a series of laboratory experiments at the ASHRAE climate chamber at Kansas State University in which large samples of college age subjects wearing standard clothing and having normal metabolic rates recorded neutralities at the same temperature irrespective of seasons. This universality hypothesis was emphasized by Fanger on the basis of two experiments in Copenhagen on a small group of "tropical travellers", winter swimmers, and meat packers. According to Auliciems:

> "It is not often realized that the claims of its universal applicability were based on remarkably limited and rather incompletely reported preference studies of only 16 travellers from Copenhagen and 32 Danes" [41, pp. 18].

Based on the results of various field studies [30, 32, 42), it is becoming increasingly difficult to dispute the role of acclimatization in determining thermal perception of inhabitants (particularly those living in hot and humid regions). In fact, in a survey of field studies conducted over last 40 years, Humphreys found that the neutral temperatures preferred by people ranged from 17 to 30°C [43]. In another study, the preferences of indoor temperatures were shown to be from about 14°C in Japan to 17°C in Norway to 21°C in Sweden, three countries with similar energy prices and similar average household incomes [44]. In a further study conducted in Bangladesh in naturally ventilated buildings (with negligible air movement), the preferred air temperature of people performing sedentary activities and wearing clothes with a 0.5 clo value, was found to be 28.9°C. This temperature is significantly higher than the value predicted using Fanger model [45]. Empirical studies have also shown that human perception of thermal comfort is somewhat dependent on the outdoor temperature: "People are attuned to outdoor events, and thermal satisfaction is maximized when indoor conditions vary according to seasonal and weather conditions" [41]. The results from these field studies suggest that people may have a tendency of adjusting to the climatic conditions. Thus the notion of universality of thermal comfort and its endorsement by international standards need to be critically reevaluated:

> "The hypothesis has been extrapolated as equally applicable to human beings around the world regardless of race, culture or climatic experience (Fanger 1973a, b). Certainly the hypothesis is still being fostered by the International Standard Organization 7730 (1984), equipment manufacturers' handbooks, and the prestigious ASHRAE (1992) handbook" [41, pp. 16].

C.4.3 MECHANICAL VERSUS NATURAL CONTROL

The models and standards of thermal comfort are based on the underlying assumption of a controlled environment. There are two aspects of this assumption which need further examination as they have direct implications on the expectations of the people in such an environment:

- Is it reasonable to apply the standards developed for mechanically controlled buildings to naturally ventilated indoor environments?

- Is it reasonable to ignore the potential effects of positive or negative connotative associations with a specific building service technology or building construction approach on people's perception of air quality and thermal environment?

The first question is particularly important in the context of those countries where only a small percentage of buildings are equipped with mechanically controlled environmental systems. The present international standards lead to the rather questionable conclusion that the majority of population in these countries are *de facto* living in substandard environments.

Two studies directly compare thermal comfort perception of two groups of people (one working in naturally ventilated buildings and the other in air-conditioned buildings) with identical cultural, climatic and linguistic background. In the study conducted in Singapore, the neutral temperature was found to be 28.5°C in naturally ventilated buildings, but only 24.2°C in air-conditioned buildings [32]. In a similar study conducted in Thailand, "it was found that the upper temperature bound for a Thai comfort standard, instead of being the currently accepted level of 26.1°C, should be as high as 31°C for office workers accustomed to naturally ventilated spaces, and as high as 28°C for those accustomed to air-conditioning" [30]. As people spend significant amount of time in indoor environments, one might explain these significant differences as the result of the previously mentioned acclimatization effect. Nonetheless, one might also speculate that the "total environmental quality" in a naturally ventilated building represents a radically different evaluation context, thus also affecting the overall calibration of thermal expectations.

This speculation is also somewhat relevant to the second question above. The presence of negative associations with mechanically conditioned environments are well-documented [15, 41]. It is conceivable that peoples' dissatisfaction with certain indoor climatic conditions is in part due to their negative view of the mechanical equipment, absence of personal control, sealed windows etc. We will further explore this notion in the following discussion of comfort and pleasantness.

C.4.4 COMFORT AND PLEASANTNESS

Thermal neutrality in the previously mentioned ASHRAE thermal sensation scale denotes a thermal condition in which people do not wish the environment to be warmer or cooler. However, as Kuno mentions, "there are situations when we can feel pleasantly cool or warm" [46]. Following this line of thinking, Kuno developed a two-dimensional model of thermal sensation to clarify the distinction between comfort and pleasantness. According to this model, the experience of thermal pleasantness results from body’s physiological inertia in dealing with quick (or discontinuous) changes in ambient conditions that are initially experienced as uncomfortable. As a consequence, one must experience the "uncomfortable zone" before entering into the "pleasant zone". According to Kuno, this two-dimensional nature of thermal sensation semantics is clearly expressed in Japanese language, where "Dan" and "Ryou" involve connotative references to the experiential hues of thermal pleasantness.

The importance of "differential stimuli" for the underlying physiological and psychological basis of perception have been known for a long time. Previous research has emphasized the importance of differential sensory information for visual and acoustical perception [3]. Still, the prevailing paradigm of active ("power-operated") HVAC systems has been to strictly provide and maintain the neutral thermal state according to the "one-dimensional" thermal sensation scale of the classical thermal comfort theory.

In this context, Kuno’s most valuable contribution may be his reference to the potential of passive building design approaches which rely on the utilization of daylight and solar radiation, contextually adopted building massing and orientation, clever enclosure design including windows for natural ventilation and shading devices, evaporative cooling methods, use of thermal mass inertia for dynamic load shifting, etc. There is no doubt regarding the superiority of these passive techniques in view of energy conservation and ecological sustainability. However, a "passive system cannot eliminate discomfort completely … If the degree of discomfort is used for evaluation of environment, the passive system can never be superior to the active system" [46]. Kuno suggests that, in order to have a fair comparison between active and passive systems, one must take pleasantness into the consideration, as "neutral environments have no pleasantness". Kuno believes - probably correctly - that arguments pertaining to energy conservation and global environment will not change the preferences of those adopted to actively conditioned environments. So he suggests that "health" should be used as an argument, and that "it is better for healthy people to experience a little discomfort".

We sympathize with Kuno's position, although we can literally visualize flocks of "experts" that ask for the exact definition of pleasantness together with a precise numeric scale and an extensive statistical analysis of the correlation of pleasantness index with measurable health parameters. Alas, even if all that could be demonstrated, the "experts" would probably guaranty that active systems could be adapted to emulate the natural fluctuation of passive systems in a much more "reliable" and "optimized" form (meanwhile applying the same basic energy-intensive technologies).

Let us afford one more speculation here. We referred previously to the SBS in cases of highly controlled and hermetically sealed indoor environments. On the other hand we mentioned the comparatively positive evaluations of naturally ventilated buildings. It is not far from human ecology's notion of "Uexküll-transformation" if one suggests that minor levels of discomfort may be lesser of a cause for negative evaluation and complaints if they are not associated with incompetent design and poor maintenance, but with the "natural" forces of environment. As was already known to Chuang Tzu over two millennia ego:

> "If someone is crossing a river in a double-hulled vessel and an empty boat comes and strikes against it, even though he may be a quick-tempered person, he will not be angry. But if there is a person in the boat he will shout to him to steer clear. If his first shout goes unheeded, he will shout again. If the second shout goes unheeded, he will shout a third time, and that will certainly be followed by a stream of abuse. In the previous instance he did not get angry but in the present instance he is angry, because the previous boat was empty but this one has a person in it" [47, pp. 190].

C.4.5 ANTHROPOLOGICAL PERSPECTIVE

In a refreshingly original contribution, Prins deals with air-conditioning from a cultural and ethical perspective. He questions the notion that "air-conditioning makes life in hot places more agreeable". In fact he sees the trust of classical thermal comfort research as "pseudo-scientific procedures applied to value judgement" and "trapped inside its normative framework" [19, 48]. According to this view, the demand for space cooling by North Americans (and those affected by their "cultural imperialism") cannot be derived from physiologically grounded essential ("Category I") human needs but must be explained instead as the result of a self-reinforcing process of cultural signification and addiction. The cultural significance is seen in the associative message of air-conditioning: "For just as powerfully as it pushes away the shadows of the past, the poor of the present and the hostility of Nature's cycles, air-conditioning exuberantly expresses the achievement of the American dream, its message adding technological to agricultural abundance" [19]. Its addictive power lies in air-conditioning's capability to rapidly teach the body "to hate the heat". Prins sees in physical addiction to air-conditioned air "the most pervasive and least noticed epidemic in modern America".

In this context, Stern formulates a significant question: "if coolth is an acquired preference, what are the resistances to reversing it?" [19]. Besides the persuasiveness of the evocative power of American consumer culture and physiological acclimatization phenomena, other - socially originated - resistances create, according to Stern, barriers to reducing space cooling demand:

> "Cities create new addicts. By an ingenious positive feedback system, air-conditioning heats the outside air, creating demand for air-conditioning among people who did not want it before. Competition enforces addiction. … Competition ratcheted up the standard of coolth, and keeps it there. And major long-term social transformations perpetuate addiction. Air-conditioning was responsible in considerable part for the migration of millions to the Sun Belt of the American south and west. These populations now depend on air-conditioning, and express their dependence through their large and growing cadre of elected representatives, who are motivated by constituent pressure to vote against energy taxes, restrictions on consumption of electricity in summer, or any other policy option that would raise the cost or limit the availability of coolth" [49].

We believe it is a mistake to label thermal comfort research as "pseudo-scientific", but it would equally be a mistake not to seriously consider compelling evidence implying possible social and cultural "conditioning" of human preferences and expectations pertaining to the indoor climate. In particular, Stern's reference of a "positive feedback" reminds on the implications of another important and equally wasteful mass industry of twentieth century, namely the automobile industry. Here again, the popularization of a technology was accompanied by an extensive cultural conditioning enforcing positively charged connotations (mobility, independence, freedom, etc.). And just as air-conditioning in the "Sun Belt", the automobile industry made forms of habitation and commuting possible that entirely rely on it and thus perpetuate its existence [36, 50, 51].

C.5 EPILOGUE

From our discourse, a rather unsatisfactory view of the conventional HVAC technology emerges:

- Its aim at provision of often centrally controlled and uniform thermal conditions in indoor spaces is inherently problematic considering the differential and dynamic nature of inhabitants' ecological potency.
- It relies almost exclusively on a thermal comfort science which, despite many valuable contributions to our understanding of people's thermoregulatory system, is still limited and nearly static in capturing relevant environmental and personal parame-

ter and is inconclusive in terms of the universal validity of its statistical predictions regarding desirable thermal regimes for indoor environment.

- In its first-cost dominated commercial realizations, it has in many instances difficulties in providing even that limited and narrowly defined set of environmental conditions and controls for which it is supposedly designed.
- It operates in a wasteful manner, is energetically entropic, and contributes significantly to environmental degradation. It is a "*brute force*" engineering solution which undercuts the demand for more effective (e.g. passive) "soft energy" technologies: It may be cheap to build, but "ecologically, financially and ultimately morally expensive to run" [19].

The case for the non-sustainability of this circumstance becomes even stronger, if some current global socio-economic tendencies and developments are considered:

- Population growth, already a serious concern in the sixties [13], has reached devastating dimensions. An increasing number of countries (particularly in the rapidly developing Asia-Pacific region) strive to reach living standards and styles set by industrialized countries, thereby uncritically adopting similar energy intensive and wasteful approaches to environmental control. Apparently the combined "cola- and auto-colonization" impact has left no room in minds and actions for Gandhi's wisdom of *atma-nirbharta* (self-reliance), the most fundamental of all recipes for sustainable development.
- The fragile nature of the air-conditioning technology (similar to the equally energy-hungry automobile industry) and the aforementioned *circulus vitiosus* of a *brute force* engineering approach and its addictive power in generation of demand poses a constant thread to global socio-political stability. The operation "Desert Storm" was a telling pretaste of what is at stake politically: "By 2020, if present trends continue, over two-thirds of world oil will be pumped from the Middle East, compared to just a quarter today" [52, pp. 5].
- The continuation and further spread of the current practice in building construction and mechanized indoor climate control undoubtedly intensifies the degradation of already stressed sensitive ecological systems. A major portion of primary energy consumption in industrialized countries is due to heating, cooling, ventilating, and

lighting of buildings. Moreover, construction, operation, and demolition of buildings constitutes the largest source of CO_2 emission in these countries. Recent proposals and actions toward oil exploration in the last heretofore protected regions in North America or elsewhere are deeply troubling indications of the ongoing ecological destruction.

All this, and the current - rather regressive - developments in environmental matters and policies may cause one to believe in the hopelessness and futility of efforts toward environmentally responsive building design methods and indoor climate control strategies. In fact, it appears that the latter would only have a chance in the rather unlikely case that long-term ecological thinking and ethical considerations would prevail. In the face of circumstances that appear to render resignation inescapable, we can only repeat the old master's wisdom [53, pp. 136]:

"... Let us hire a sacred fool,
and fill up the well with snow together".

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